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Assessing outdoor thermal comfort and activities of the elderly in urban parks: A case study in Xiamen, China

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Abstract: The elderly are the primary users of urban parks, and thermal environment plays an important role in quality of life. However, existing research on outdoor thermal comfort (OTC) has given limited attention to the elderly in hot-summer and warm-winter (HSWW) regions. In this study, field surveys, including meteorological measurements, questionnaires, and activity observations were conducted to assess OTC of the elderly. Physiological equivalent temperature (PET) was calculated, and the results indicated that: 1) Neutral PET (NPET) of the elderly was 23.5°C, with neutral PET range (NPETR) of 19.01-27.98°C. Preferred PET was 25.5°C, and 80% thermal acceptability range (TAR) was 7.2-21.45°C. 2) Among influencing factors, physical factors were the most important, followed by psychological and individual factors, while social factors had limited effects. 3) A multiple linear regression model was used to determine the weights of factors affecting thermal sensation, thereby establishing a high-performance predictive model. 4) In spring and autumn, PET and attendance exhibited a quadratic relationship. In summer, attendance was negatively correlated with PET, and it was very low when PET exceeded 37°C. 5) The elderly primarily alleviated discomfort by regulating thermal radiation when facing thermal stress. These findings provide valuable references for the optimized design of urban parks, aiming to better meet thermal demands of the elderly and promote healthy aging.

Keywords: Outdoor thermal comfort (OTC); The elderly; Activities; Urban parks; Physiological

equivalent temperature (PET)

Introduction

The United Nations predicts that by 2050, nearly one-third of global population will be aged 60 or older(World Health Organization 2022). Survey data from the National Bureau of Statistics of China show that proportion of population aged 60 and above has reached 21.1%, and this figure is expected to rise to 30% by 2040(National Bureau of Statistics 2026). Studies have shown that 67% of the elderly prefer engaging in activities in urban parks(Dong et al. 2013). As primary users of urban parks, the elderly can benefit substantially from participation in activities, which can enhance subjective well-being(Murtagh et al. 2015). Against the background of global warming, the elderly are more susceptible to heat-related health issues because of declines in thermoregulatory mechanisms. Therefore, outdoor thermal comfort (OTC) has become a key factor affecting activities and quality of life among the elderly(Ma et al. 2021; Zhang et al. 2021).

American Society of Heating, Refrigerating and Airconditioning Engineers (ASHRAE) defines thermal comfort as "a state of consciousness in which individual is satisfied with thermal environment"(ASHRAE 2017). OTC is a comprehensive perception shaped by the combined effects of physical, individual, psychological, and social factors. Among them, physical factors exert the greatest influence. Physical factors include air temperature (T_a), relative humidity (RH), wind speed (V_a), and solar radiation (G), each of which affects OTC to different extents(Li et al. 2020). Studies indicated that physiological signals, such as skin temperature and heart rate(Nakayoshi et al. 2015) vary in response to thermoregulatory process and can therefore serve as effective indicators for predicting OTC. Due to

differences in individual and social characteristics, they also exerted effects on OTC(Baquero Larriva and Higuera 2020; Yuan et al. 2023; Wang et al. 2025). Since thermal comfort was defined as a "psychological state," psychological factors cannot be ignored. Thermal experience(Yao et al. 2018), thermal expectation(Lam et al. 2018) are psychological factors most frequently discussed in previous studies. In addition, environmental characteristics, spatial type, urban greening, and water features are all important factors affecting OTC(Hu et al. 2025).

Urban parks are important open spaces where the elderly engage in activities, socialize, and maintain physical and mental health. However, thermal perception is a critical factor affecting activities and attendance(Niu et al. 2022). Comfortable environments will increase participation and positively affect on frequency and duration of activities(Morris et al. 2019). Encouraging participation in outdoor activities may reduce the elderly's reliance on indoor electrical appliances, thereby contributing to lower energy consumption. Therefore, creating favorable environments can actively respond to aging problem. With increasing age, physiological functions, such as metabolism and thermoregulation gradually decline, leading to reduced thermal sensitivity(Matzarakis et al. 2020). Previous studies reported that there are significant differences in thermal perception between the elderly and younger adults(Baquero Larriva and Higuera 2020). Xiong found that although no difference was observed between the elderly and younger adults at neutral temperature, the elderly were less sensitive to temperature changes(Xiong et al. 2019). Owing to decrease in metabolic rate, the elderly tend to prefer warmer environment(Lam et al. 2021). Age-related physiological changes are further reflected in weakened thermoregulatory responses(van Hoof et al. 2017). In addition, declines in cognitive ability may reduce capacity to cope with thermal stress, increasing the risk of heat-related health(Martins et al. 2020). According to China's

architectural climate zoning standards, research on this topic has primarily focused on severe cold(Jin et al. 2019; Bai and Jin 2023; He et al. 2024), cold(Ma et al. 2021; Yao et al. 2022; Yuan et al. 2023; Song 2024; Xue et al. 2024), hot-summer and cold-winter (HSCW) regions(Li et al. 2022; Wang et al. 2023; Qin et al. 2025) .

Most studies on OTC of the elderly focused on identifying thermal benchmarks and influencing factors. Neutral temperature varies across climatic zones, and this difference are associated with geographical latitude. Neutral temperature tends to be higher in lower-latitude regions, while neutral temperature range is broader in cold regions. Influenced by climatic zones and seasonal variations, OTC demands also exhibit differences(Qin et al. 2025). For example, the elderly in Lhasa prefer greater solar radiation in winter, whereas they prefer lower V_a in summer and autumn(Yao et al. 2022). In hot and humid regions, the elderly may still be willing to receive solar radiation under appropriate shading conditions(Fang and Hu 2019). In addition, scholars have examined the relationship between outdoor thermal comfort and activities. Yung found that the choice of open spaces was mainly affected by activity level(Yung et al. 2019). Wang also found that activity intensity and content significantly affected thermal perception(Wang et al. 2023). Compared with males, females were more sensitive to cold and more tolerant of thermal stress(Jin et al. 2019). It's important to note that even when the elderly feel thermally comfortable, they may still be exposed to thermal risks(Qin et al. 2025). To date, research specifically addressing OTC of the elderly in HSWW region remains limited. HSWW regions are characterized long summers and frequent heat waves, which may place the elderly at greater risk. Therefore, greater attention should be given to OTC of the elderly in order to fill this gap.

In respond to this gap, we selected the elderly in Xiamen as research population and employed

meteorological monitoring, questionnaire survey, and behavioral observation to conducted an in-depth assessment. The objectives were to: (1) quantitatively assess OTC threshold of the elderly; (2) identify the influence of physical, individual, social, and psychological factors on thermal perception; (3) explore the relationship between thermal comfort and activity characteristics. The results reveal the complex relationship between thermal comfort and behavioral characteristics, and provide guidance for the design of age-friendly environments.

Methods

Study area

Xiamen (24°43'N, 118°10'E) locates in southeastern Fujian Province, China. It has a subtropical marine monsoon climate, characterized by hot, humid summers and mild winters (Fig. 1a). Meteorological data show that average annual T_a is 22°C and average annual RH is 77% in Xiamen. The highest monthly average T_a occurs in July (28.5°C), whereas the lowest occurs in January (13.3°C). Rapid urbanization has further exacerbated urban heat island effect in Xiamen(Jia et al. 2023). In August 2019, an extreme high temperature of 39.6°C was recorded by meteorological authority. In July 2024, Xiamen experienced a rare 12 consecutive days of high temperatures, breaking the record for the longest duration of extreme heat.

In this study, Zhongshan Park, Songbai Park, Fire Park and Jingxian Park were selected as study sites (Fig. 1b). The reasons for selecting these parks are: 1) They are popular destinations for the elderly's daily activities, and high visitor traffic ensures adequate questionnaire samples; 2) These parks include comprehensive and community parks, enabling a more comprehensive investigation of OTC. Preliminary surveys found activity spaces most frequently used by the elderly were primarily open squares and shaded

spaces. Therefore, representative open spaces (OS) and shaded spaces (SS) were selected for measurements (Fig. 1c).

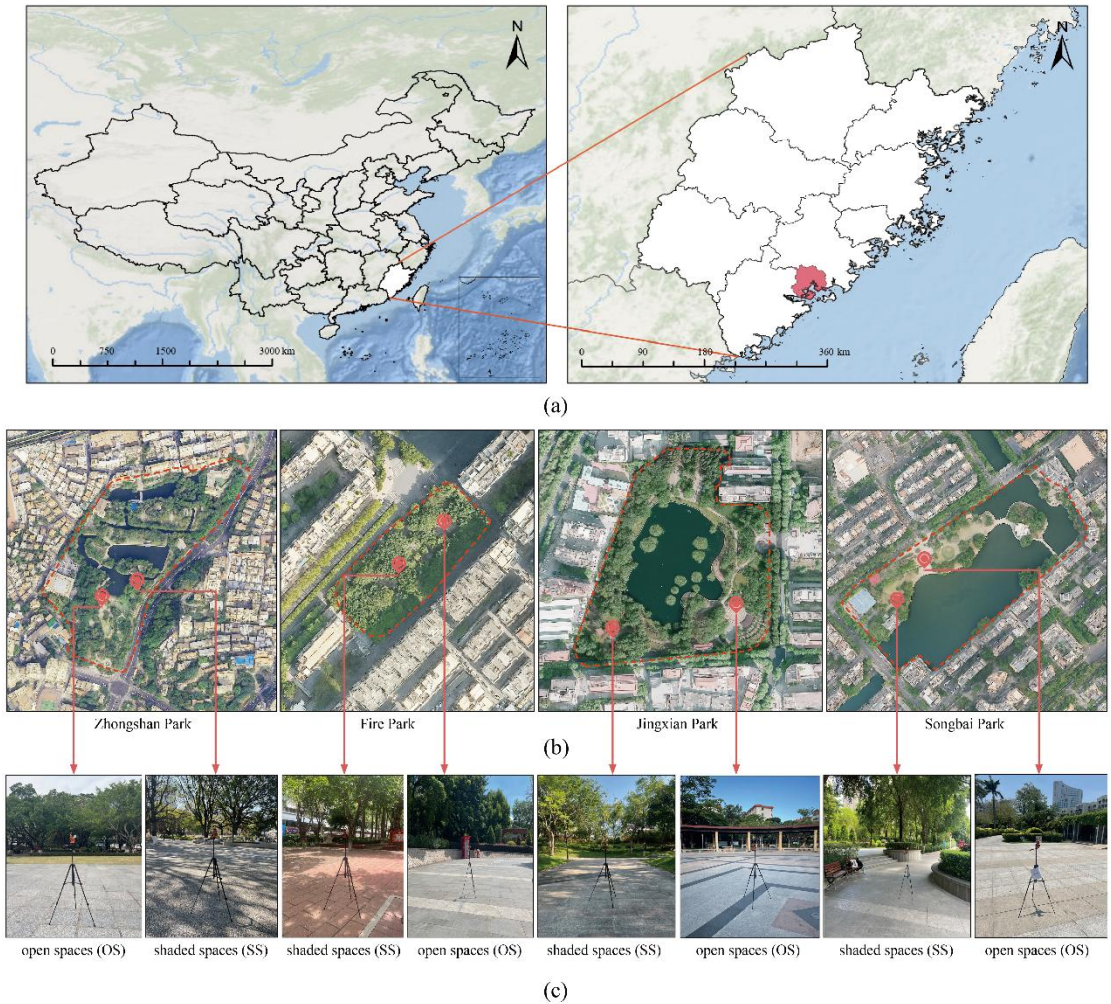


Figure. 1 Study area. **(a)** Geographical location; **(b)** Site location; **(c)** Measured spaces

Experimental design

Meteorological measurement

Experiment was conducted from January to December 2025, covering all seasons in Xiamen. All surveys were carried out under sunny and rain-free conditions, with monitoring conducted from 8:00 to 18:00. Experiment used Kestrel 5400 to monitor meteorological parameters, including T_a , RH , V_a , and T_g (Table 1). The instrument was tested and calibrated prior to the initial survey. It was mounted on a

tripod at a height of 1.5m above ground, and all parameters were recorder at 1min intervals.

Table 1 Meteorological measuring instruments

Instrument	Parameter	Range	Accuracy	Measurement interval
Kestrel 5400	Air temperature (T_a)	-29°C-70°C	±0.5°C	1min
	Relative humidity (RH)	0-100 %	±2 %	1min
	Wind speed (V_a)	0.6-40 m/s	±3 %	1min
	Globe temperature (T_g)	-29°C-60°C	±1.4°C	1min

According to ISO 7726 standard(International standard 7726 1998), mean radiant temperature (T_{mrt}) was calculated as:

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

Where T_g is the globe temperature (°C), V_a is the wind speed (m/s), T_a is the air temperature (°C), D is the globe diameter ($D = 0.05$ m), and ϵ is the emissivity of the globe ($\epsilon = 0.95$).

Questionnaire survey

Concurrent with the microclimatic monitoring, the elderly aged 60 and above were recruited for investigation. Before questionnaire, respondents were required to spent at least 20min outdoors. During the survey, researchers provided detailed explanations when respondents encountered difficulties in filling out the questionnaire. The questionnaire comprised three sections: personal information, thermal perception and adaptative behavior (Appendix S2). The first section collected gender, age, height, weight, length of residence (LoR), frequency of activity (FoA), means of transportation (MoT), education background, monthly income, purpose of activity (PoA), duration of outdoor exposure (DoE), clothing, and activity type. Clothing insulation was calculated according to ASHRAE Standard 55-2017. In addition, adjusted metabolic rates for the elderly were adopted, with 1Met = 43.1 W/m² for males and

38.6 W/m² for females(Chindapol et al. 2017).

The second section focused on thermal perception, including thermal sensation vote (TSV), thermal comfort vote (TCV), thermal acceptability vote (TAV) and thermal satisfaction. TSV was assessed using ASHRAE-recommended 7-level scale. TCV and thermal satisfaction was measured on a 5-level scale, while TAV was evaluated on a 4-level scale. The third section investigated thermal adaptive behaviors. During the experiment, researchers selected locations with unobstructed views of spaces and used high-resolution camera to record activities every 30 min. This method provided a visual record of content and quantity of activities. The elderly were identified based on physical characteristics and behavioral patterns.

Thermal index

Currently, 165 thermal indices are available for predicting thermal comfort. Physiological equivalent temperature (PET) have been extensively used in outdoor studies(Zheng et al. 2025). PET is an index developed by Höppe based on Munich Individual Energy Balance Model (MEMI)(Höppe 1993). It is defined as the air temperature at which core and skin temperature of a standard person under specific outdoor conditions are equal to those in a typical indoor environment(Potchter et al. 2018). As a comprehensive indicator of effective thermal sensation, PET was therefore selected to evaluate OTC in this study.

Data analysis

All data were analyzed using Microsoft Excel 2020 and SPSS 22.0. First, linear regression and probit regression were employed to determine thermal comfort thresholds. Second, ordinal logistic regression was used to examine the effects of predictor variables on thermal perception. Third, stepwise

regression was conducted to quantitatively analyze the influence of key factor on thermal perception. All statistical figures were generated using Origin 2022 software.

Results

Descriptive analysis

Respondent attributes

A total of 4818 valid questionnaires were collected, including 906 in winter, 1283 in spring, 1345 in summer, and 1284 in autumn. Demographic data indicated a balanced gender distribution, with males and females comprising 52% and 48%, respectively. The average age was 68 for males and 66 for females. All respondents were capable of adapting to local climate and accurately evaluating outdoor thermal environments.

Thermal environment characteristics

In OS spaces, the average of T_a (winter: 18.6°C, spring: 28.0°C, summer: 34.9°C, autumn:23.9°C), T_g (winter: 21.9°C, spring: 29.0°C, summer: 37.4°C, autumn:25.2°C), and T_{mrt} (winter: 27.0°C, spring: 30.7°C, summer: 43.1°C, autumn:28.2°C) were higher than SS spaces across seasons. This may be because OS spaces were open plazas fully exposed to solar radiation, characterized by highly reflective hard paving. In OS spaces, the average RH showed a significant decreasing trend from winter to autumn, in contrast to the pattern observed in SS spaces. In winter and spring, the average V_a in SS spaces was higher than OS spaces. In summer, the highest V_a was observed in SS spaces (2.2 m/s), however, the average V_a in both spaces was consistent at 0.6 m/s (Table S3). Overall, most meteorological parameters exhibited pronounced seasonal variations.

Thermal environment evaluation characteristics

In winter, "slightly cold" was the most frequently response, followed by "moderate". In spring, most elderly reported feeling "slightly hot", with 37% selecting "moderate" and 11% selecting "hot". In summer, no respondents reported TSV below "moderate". The highest proportion of TSV was "slightly hot", followed by "hot" and "very hot". In autumn, the proportions of "slightly cold" and "moderate" were higher, showing similar patterns observed in winter (Fig. 2a).

TCV patterns were similar in winter and spring, with "moderate" being the most frequent option. Compared with winter, the proportions of "comfortable" and "very comfortable" were higher in spring. In summer, the proportion of respondents reporting "uncomfortable" increased to over 50%. By autumn, the proportion of "comfortable" increased significantly (Fig. 2b). The comfortable state corresponded $TSV = -0.14$, at which $TCV = 0.029$. When TSV ranged from -0.51 to 0.22, TCV remained above 0 (Fig. 2c).

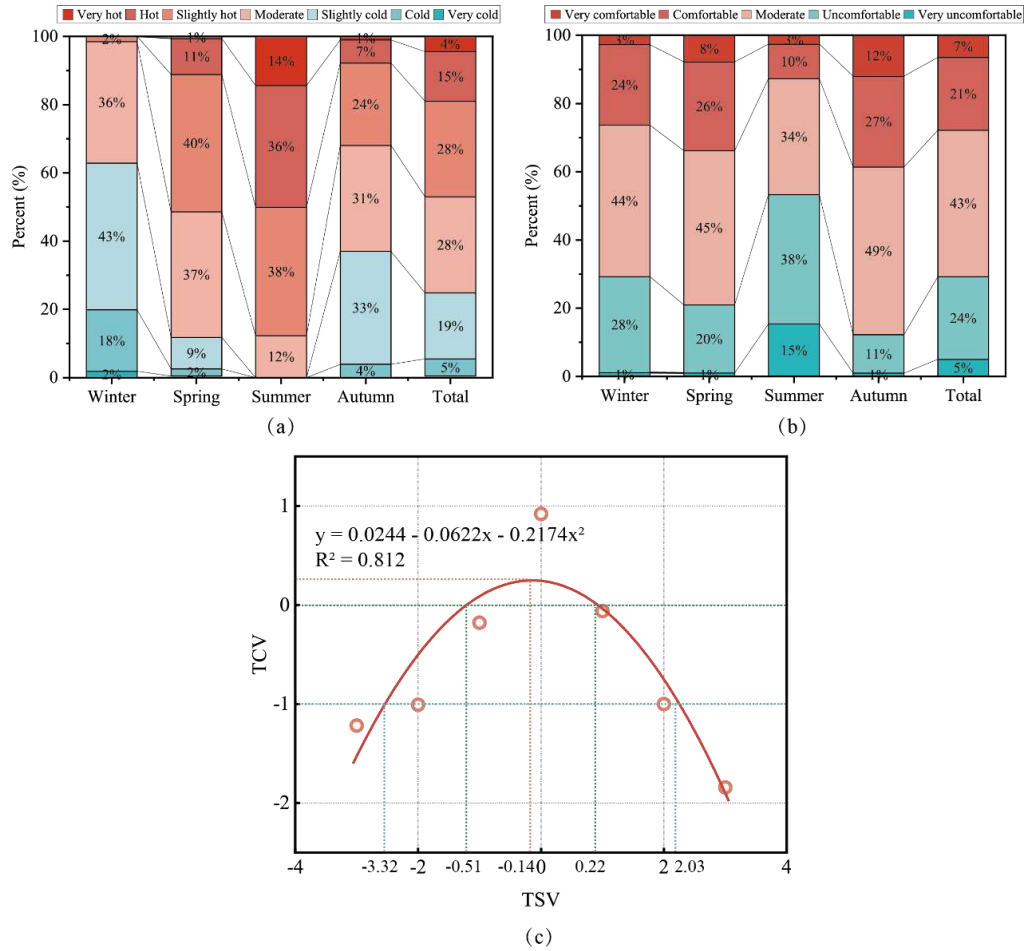


Fig. 2 TSV (a) and TCV (b) and correlation between TSV and TCV (c)

Quantitative evaluation of outdoor thermal comfort

Neutral temperature Neutral temperature range

Neutral temperature refers to the temperature at which individuals feel neither cold nor hot(ASHRAE 2017). Mean TSV corresponding to each 1°C PET interval was calculated and fitted using a linear regression (Fig. 3). When $mTSV = 0$, corresponding PET were defined as neutral PET (NPET). The results indicated that NPET of the elderly was 21.1°C in winter, 23.9°C in spring, 24.6°C in summer, 23.29°C in spring, and 23.5°C overall.

When $mTSV$ ranges from -0.5 to 0.5, corresponding temperature range is defined as neutral temperature range, namely neutral PET (NPETR)(Cheung and Jim 2017).The results showed that

NPETR were 16.52-25.7°C in winter, 19.95-27.82°C in spring, 17.97-28.31°C in summer, 19.55-27.05°C in autumn and 19.01-27.98°C overall (Fig. 3).

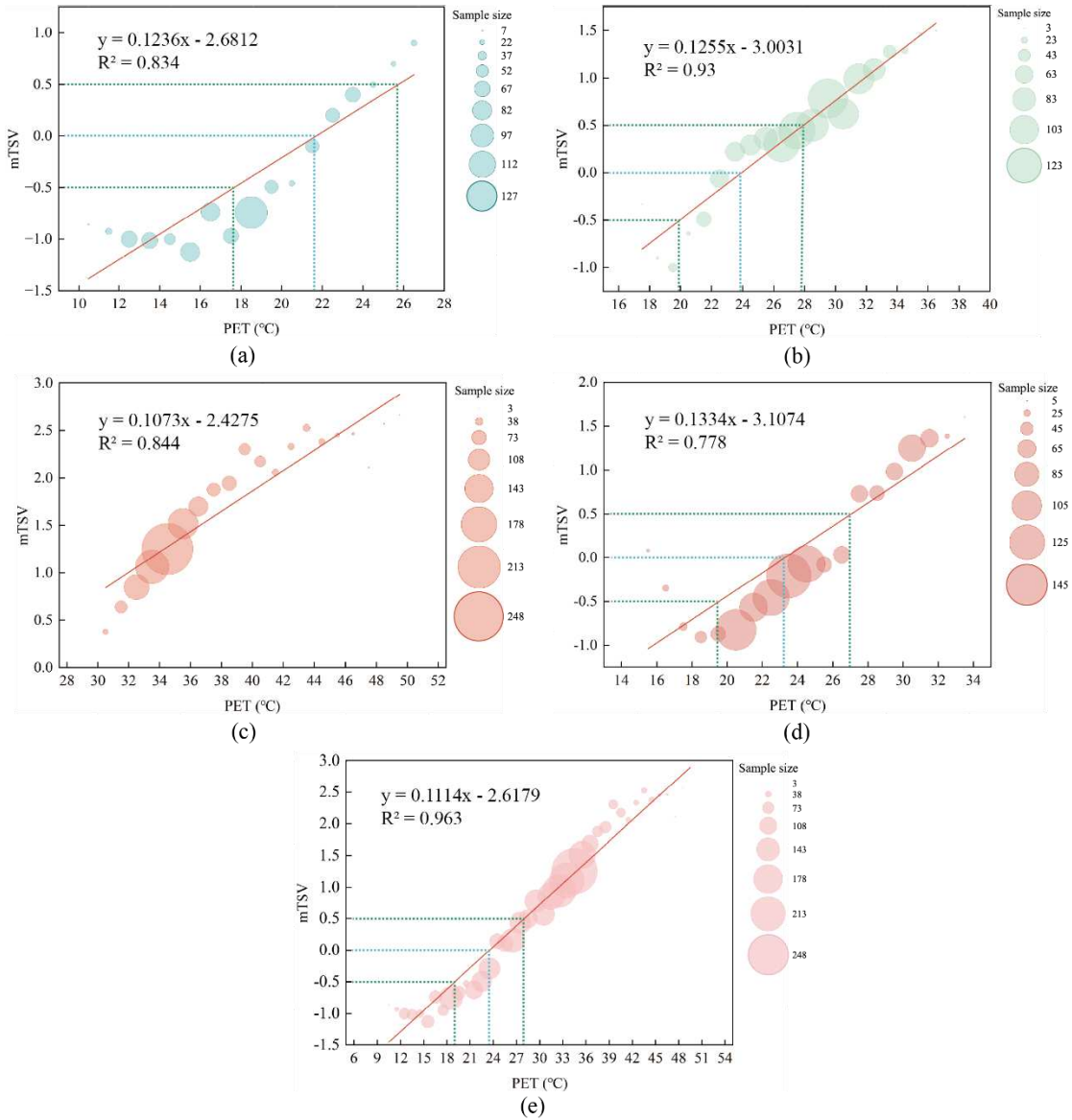


Fig. 3 Relationship between PET and mTSV: (a) Winter, (b) Spring, (c) Summer, (d) Spring, (e) Overall.

Preferred temperature

Preferred temperature is that desired by individuals, also known as the ideal temperature. A probit regression model was applied to thermal preference votes. Each 1°C PET interval was divided into groups, and the percentage of "wanting cooler" and "wanting warmer" responses was calculated within

each group. The intersection of the two logistic curves was defined as preferred temperature(Cheung and Jim 2017). According to this method, preferred PET was 25.5°C, which was 2°C higher than NPET (23.5°C), indicating that the elderly preferred warmer environments (Fig. 4a).

Thermal acceptability range (TAR)

ASHRAE standard 55 defines TAR as the temperature range considered acceptable by at least 80% (normal condition) or 90% (strict condition) of respondents(ASHRAE 2017). In other words, a temperature is regarded as unacceptable when only 20% or 10% of respondents reporting dissatisfaction. In this study, 80% TAR was 7.2-24.45°C (Fig. 4b).

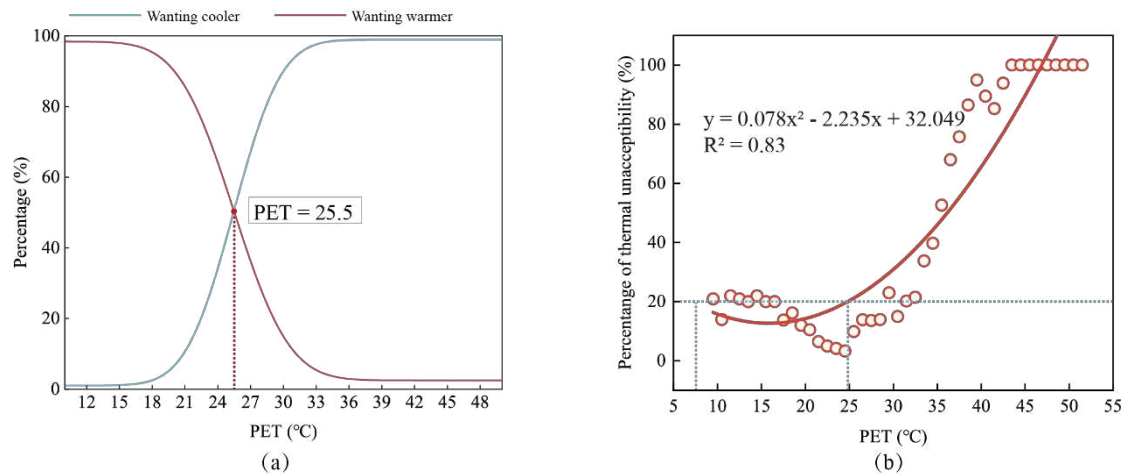


Fig. 4 Preferred temperature (a) and relationship between thermal unacceptable rate and PET(b)

Predicted percentage of dissatisfied (PPD)

Predicted percent dissatisfied-predicted mean vote (PPD-PMV) is widely used to estimate the proportion of respondents experiencing thermal discomfort. According to ISO 7730 standard, thermal discomfort occurs when TSV falls within the ranges of -2 to -3 or +2 to +3. Based on this criterion, a predictive model for the dissatisfaction rate was established. The fitted equation was as follows:

$$PPD = 100 - 99.96 \cdot \exp(-0.0805 \cdot TSV^4 - 0.0289 \cdot TSV^2) \quad (R^2 = 0.97) \quad (2)$$

Factors affecting thermal perception

Thermal perception is affected by various factors, including physical, individual, social, and psychological factors. Therefore, we examined the relationships between thermal perception and influencing factors to infer influence of physical environment, individual characteristics, social background, and psychological factors on thermal perception.

Physical factors

In winter, TSV was correlated with T_g and RH , with T_g playing a dominant role. TCV was influenced by T_g and RH , with T_g showing positive effects on TCV and RH showing opposite pattern. In spring, T_a , T_g , and RH were significantly correlated with TSV. T_a contributed the most to the positive variation in TSV, with T_g and RH exhibiting progressively weaker effects. Among physical factors, only V_a significantly affected TCV. In summer, T_a and T_g were correlated with TSV but negatively correlated with TCV, with T_a exerting stronger effects on both variables than T_g . Furthermore, TAV was significantly influenced by T_a , T_g , and RH , with a negative correlation observed. In autumn, TSV was positively affected by T_g but negatively affected by RH , whereas TCV was significantly correlated with T_a and T_g in opposite directions (Fig. 5).

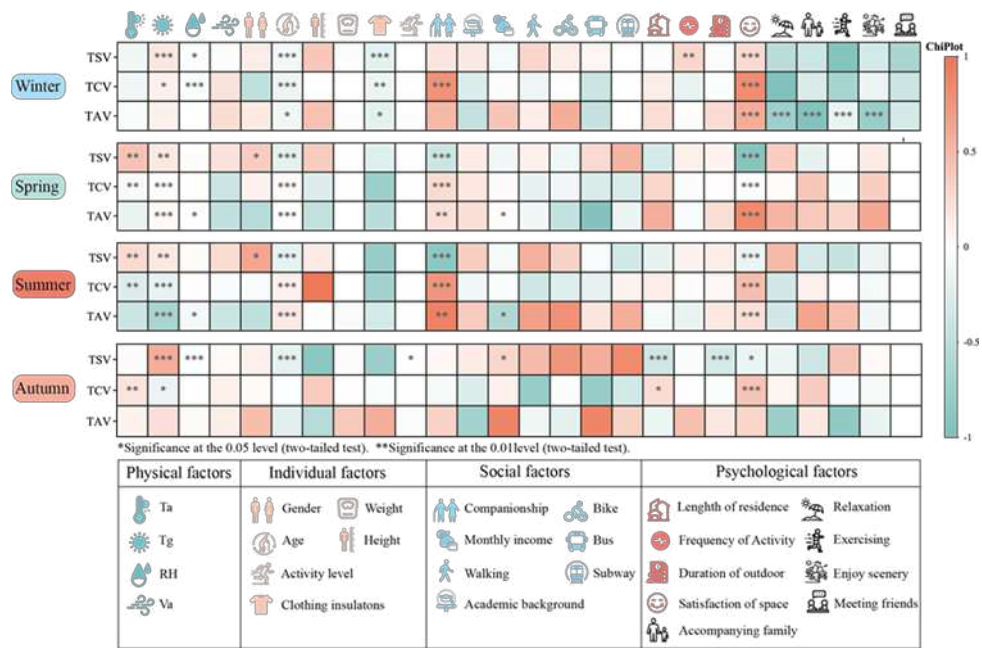


Fig. 5 Results of ordinal logistic regression model regression estimate

Individual factors

In winter, TSV, TCV, TAV were negatively correlated with age and clothing insulation, among which clothing insulation had a more pronounced effect on thermal perception. In spring, TSV was negatively affected by age but positively affected by height, clothing insulation, and activity level. TCV showed positive associations with age and activity level, yet a negative association with clothing insulation. Moreover, clothing insulation was inversely related to TAV. In summer, TSV was significantly influenced by gender and age, with age showing a negative correlation with TSV. While TCV and TAV were also significantly affected by age. In autumn, only age and activity level emerged as significant predictors of TSV, with negative and positive influences, respectively (Fig. 5).

Social factors

Among the social factors examined, only companionship showed a positive correlation with TCV in winter, implying that the presence of companions enhanced thermal comfort perception among the elderly. In spring, only companionship was negatively associated with TSV, suggesting that accompanied

the elderly reported lower TSV and thus appeared more tolerant of thermal environment. In summer, companionship negatively affected TSV but positively influenced both TCV and TAV, while monthly income showed a negative association with TAV. In autumn, however, monthly income was the only social factor that positively affected TSV (Fig. 5).

Psychological factors

Among psychological factors examined (LoR, FoA, DoE, SaS, and PoA), both FoA and SaS positively influenced TSV in winter, with SaS showing a stronger effect. SaS was also positively correlated with TCV and TAV, while PoA additionally contributed to TAV. Further analysis of activity purposes revealed that "relaxation," "accompanying family," "exercising," and "meeting friends" were main purposes significantly associated with TAV. In spring, both LoR and SaS significantly influenced TSV, TCV, and TAV, with SaS exerting stronger effects across all three variables. In summer, however, only SaS significantly affected thermal perception, with its influence ranking as TAV > TCV > TSV. In autumn, LoR, DoE, and SaS showed negative correlations with TSV, whereas LoR and SaS positively affected TCV (Fig. 5).

Quantification critical factors affecting TSV

To examine the relationships between TSV and influencing factors, stepwise regression analysis was employed to select significant variables and estimate standardized coefficients, which eliminated the effects of unit differences between dependent and independent variables. The absolute values of standardized coefficients reflect the direct contributions of independent variables to dependent variables (Table S4).

In winter, TSV was influenced by psychological factors, followed by individual characteristics.

Among physical factors, only T_g exhibited a positive correlation with TSV. The relation was as follows:

$$TSV_{winter} = 0.319 + 0.024 \cdot T_g + 0.48 \cdot SaS - 0.485 \cdot clo - 0.02 \cdot Age + 0.06 \cdot FoA \quad (R^2 = 0.652) \quad (3)$$

In spring, TSV was influenced by physical, individual, social, and psychological factors, among which physical factors exerted the strongest impact, followed by individual and psychological factors.

The relation was as follows:

$$TSV_{spring} = 1.171 + 0.08 \cdot T_a + 0.052 \cdot T_g - 0.056 \cdot Age - 1.034 \cdot clo + 0.002 \cdot Met - 1.157 \cdot Companionship - 0.086 \cdot LoR - 0.176 \cdot SaS \quad (R^2 = 0.641) \quad (4)$$

In summer, TSV was primarily influenced by psychological factors, followed by physical and individual factors. The relation was as follows:

$$TSV_{summer} = 1.041 + 0.037 \cdot T_a + 0.04 \cdot T_g - 0.031 \cdot Age - 0.144 \cdot Companionship - 0.475 \cdot SaS \quad (R^2 = 0.776) \quad (5)$$

In autumn, physical factors were the primary determinants of TSV, followed by individual characteristics, psychological and social factors. The relation was as follows:

$$TSV_{autumn} = 0.101 + 0.173 \cdot T_g - 0.005 \cdot RH - 0.055 \cdot Age + 0.006 \cdot Met + 0.107 \cdot Monthly \text{ income} - 0.134 \cdot LoR - 0.091 \cdot DoE - 0.081 \cdot SaS \quad (R^2 = 0.663) \quad (6)$$

Overall, TSV was predominantly influenced by physical factors (T_a and T_g), followed by individual characteristics (age and clothing insulation). Psychological factors also exerted a non-negligible influence, whereas the role of social factors remained relatively limited. The relation was as follows:

$$TSV_{overall} = 3.567 + 0.074 \cdot T_g + 0.021 \cdot T_a - 0.008 \cdot RH - 0.064 \cdot Age - 0.14 \cdot SaS - 0.514 \cdot clo - 0.099 \cdot Companionship - 0.076 \cdot LoR + 0.01 \cdot Met - 0.069 \cdot Gender + 0.037 \cdot FoA \quad (R^2 = 0.769) \quad (7)$$

Behavioral characteristics

Activity characteristic and PET

Adjustment of activity intensity may be regarded as a form of climate adaptation. The elderly typically predetermine activity types (e.g., sitting, walking, Tai Chi, and square dancing) prior to engagement, resulting in relatively stable activity levels. In winter, the mean activity level was 66.5 W/m², with sedentary behavior constituting the largest proportion, followed by low-intensity activities. A similar distribution was observed in spring, where the average activity level was 62.9 W/m². With the arrival of summer, the average activity level decreased to 53.8 W/m², with most elderly primarily engaging in prolonged sitting or standing. In autumn, the average level increased to 57.2 W/m², accompanied by a gradual rise in the proportion of moderate-intensity activities (Table 2). Furthermore, a quadratic relationship was identified between metabolic rate (Met) and PET, with activity levels declining progressively once the temperature exceeded a critical threshold. The equation was as follows:

$$\text{Met} = 76.576 - 0.327 \cdot \text{PET} - 0.008 \cdot \text{PET}^2 \quad (R^2 = 0.776) \quad (8)$$

Table 2 Respondent's activity metabolic rate (W/m²)

Gender	Winter			Spring			Summer			Autumn		
	Min	Max	Mean±SD	Min	Max	Mean±SD	Min	Max	Mean±SD	Min	Max	Mean±SD
Male	38.6	185.3	63.9±25.9	43.1	185.3	62.2±25.7	43.1	146.5	51.6±15.1	43.1	146.5	52.2±16.9
Female	38.3	165.9	69.7±37.3	38.6	165.9	63.4±30.1	38.6	131.1	56.4±28.3	38.6	165.9	62.9±33.5
Total	38.3	185.3	66.5±31.8	38.6	185.3	62.9±28.1	38.6	146.5	53.8±22.2	38.6	165.9	57.2±26.6

Space attendance and PET

The relationship between PET and attendance varied markedly across seasons (Fig. 6). No significant association was detected in winter. A quadratic pattern emerged in spring and autumn, with attendance peaking at 24.9°C and 21.1°C, respectively, and decreasing thereafter with rising PET. In

contrast, summer exhibited a negative linear relationship, with attendance remaining very low once PET surpassed 37°C.

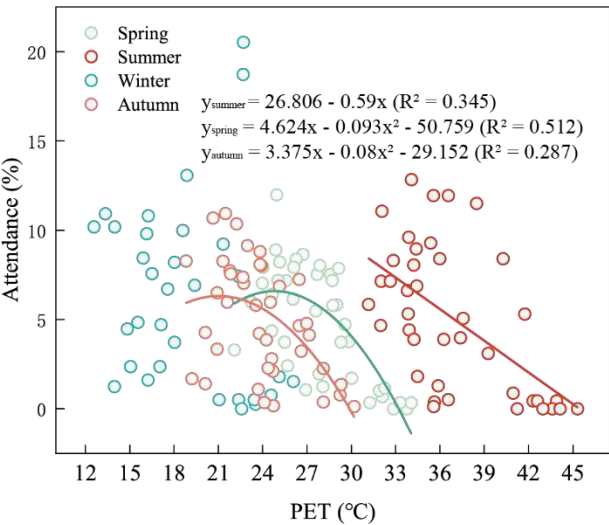


Fig. 6 Relationship between PET and attendance among seasons

Thermal adaptative behaviors

Adaptative behaviors to unfavorable thermal conditions exhibited distinct seasonal patterns (Fig. 7). In winter, "moving into sunlight" emerged as the dominant strategy (44.5%), followed by "adding clothes" (24.2%), "increasing exercise intensity" (19.3%), and "drinking hot water" (11.7%). In spring, "moving to shaded areas" ranked first, with "using a fan" and "drinking water or beverages" as secondary measures. Summer showed a similar pattern, with "moving to shaded areas" being the primary relief strategy, augmented by "using a fan" and "drinking water or beverages". In autumn, preferred strategies reverted to "moving into sunlight," "adding clothes," and "increasing exercise intensity".

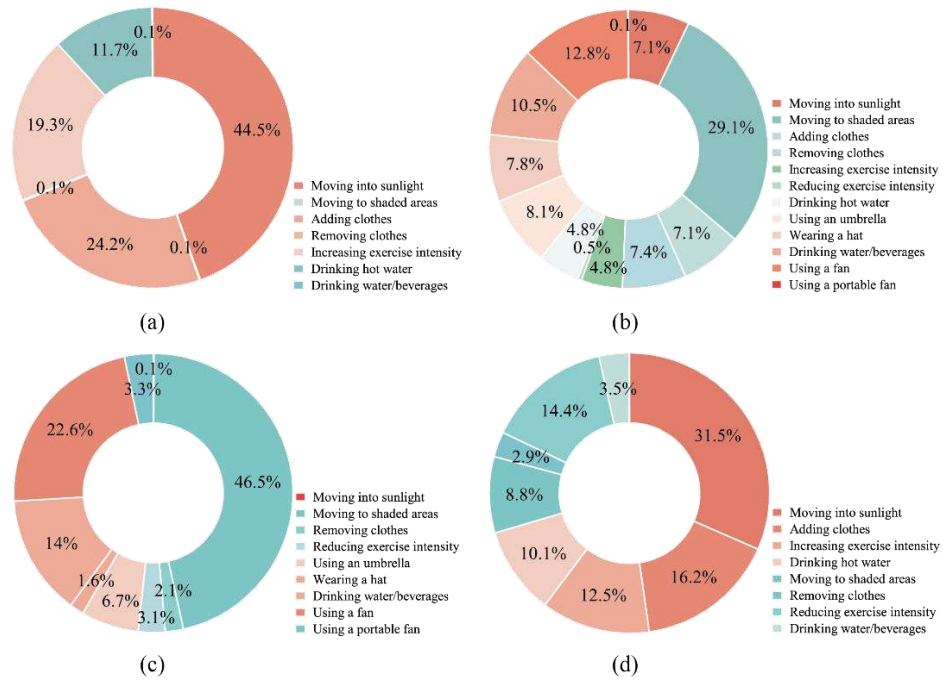


Fig. 7 Thermal adaptation behaviors of the elderly among seasons: **(a)** Winter, **(b)** Spring, **(c)** Summer, **(d)** Autumn

Discussion

Thermal benchmarks

Neutral temperature

Our study found that NPET for the elderly in Xiamen (23.5°C) was lower than Guangzhou (25.6°C) (Table 3)(Fang and Hu 2019). Despite similar climatic conditions between the two cities, this discrepancy may be attributed to differences in study settings. Guangzhou study was conducted in a nursing home, where residents may have a higher prevalence of chronic conditions and greater physiological vulnerability, potentially leading to preferences for warmer environments. Additionally, that study was conducted only during hot summer, which may also have contributed to higher NPET.

Compared with HSCW regions such as Shanghai, Huangshan, and Chongqing, NPET in Xiamen was higher by 8.82°C, 17.66°C, and 0.9°C(Wang et al. 2023; Zhou et al. 2024; Qin et al. 2025). The more

pronounced differences with Shanghai and Huangshan may be partly attributed to the wintertime data in those studies. Additionally, NPET in this study was also higher than that in cold and severely cold regions(Ma et al. 2021; Yao et al. 2022; He et al. 2024; Li et al. 2025). Comparisons across studies indicated that climatic context is an important determinant of thermal preference, suggesting that the elderly in HSWW regions may have developed both physiological and psychological acclimatization to local thermal environments. In this study, NPET was significantly higher in summer, spring, and autumn than in winter. Collectively, differences in NPET are primarily attributable to climatic zones, seasonal variations, and population characteristics.

Table 3 Comparison of outdoor thermal benchmarks among the elderly

Region	Site	Climate zone	Season	Thermal index	Neutral temperature (°C)	Neutral temperature range (°C)	80% or 90% TAR (°C)
Xiamen	Urban park	HSWW/Cfa	All	PET	21.1/23.9/24.6/23.29/23.5(Win/Spr/Sum/ Aut/A)	16.52~25.7/19.95~27.82/17.97~28.31/19.55~27.05/19.01~27.98(Win/Spr/Sum/ Aut/A)	80% TAR: 7.2~21.45
Guangzhou(Fang and Hu 2019)	Nursing Home	HSWW/Cfa	Sum	PET	25.6	23.79~27.41	90% TAR:22.62~31.15
Hongkong(Yung et al. 2019)	Park	HSWW/Cfa	Sum & Win	PET	-	-	-
Shanghai(Zhou et al. 2024)	Nursing Home	HSCW/Cfa	Win	PET	14.68	9.78~19.53	90% TAR:9.08~25.11
Huangshan(Wang et al. 2023)	Community park	HSCW/Cwa	Win	PET	5.84	0.22~11.46	80% TAR:3.32~28.91
Chongqing(Qin et al. 2025)	Open space	HSCW/Cfa	Sum& Win	PET	24.2/19.9/22.6(Sum/Win/A)	19.8~28.5/16.4~23.3/18.1~27.1(Sum/Win/A)	80% TAR:4.8~43.3;
Beijing(Li et al. 2026)	Greenway	Cold/Dwa	Sum	UTCI	25.14/24.74/24.44(S/L/M)	23.18~27.0/22.66~26.82/22.22~26.65(S/L/M)	80% TAR : ≤ 31.92/ ≤ 29.79/ ≤ 33.05 (S/L/M)
Zhangjiakou(Li et al.	Community	Cold/Bsk	Win &	UTCI	17.1/22.1/23.6/16.1	4.5~29.8/0.3~43.9/17.2~30.1/4.5~27.	80%

2025)					Spr & Sum	(Win/Spr/Sum/A)	6(Win/Spr/Sum/A)	TAR:0.1~32.9
Xi'an(Ma et al. 2021)	Urban park	Cold; Bsk/Win & PET	Cwa	Sum		13.3/20.3/13.2(Win/Sum/A)	3.1~23.2	90%
Lhasa(Yao et al. 2022)	Urban open spaces	Severely cold/Win & PET	Dwb	Sum		12.76(M);11.08(F)/25(M);22.14(F)/20.6(Win/Sum/A)	8.42~17.11(M);5.97~16.18(F)/17.85~32.14(M);16.65~27.64(F)/13.0	-
Harbin(He et al. 2024)	Urban park	Severely cold/Win		UTCI		13.3	1.4~25.2	-
			Dwa					

Note: S-sedentary behaviors, L-light intensity, M-moderate intensity; Win-winter, Spr-spring, Sum-summer, Aut-autumn, A-all season; M-male, F-female.

347 Neutral temperature range

348 In this study, NPETR of the elderly was 19.01~27.98°C. The upper limit approximated that of
349 Guangzhou, while the lower limit was 4.78°C lower(Fang and Hu 2019). Although both cities are in
350 HSWW regions, Guangzhou's average maximum T_a (32.7°C) was slightly higher than Xiamen's (32.3°C),
351 implying greater heat adaptation. The year-round design of this study, versus the summer-only
352 Guangzhou data, and differing age definitions for the elderly may also explain the discrepancy.

353 In HSCW regions, the upper and lower limit of NPETR in Huangshan(Wang et al. 2023) and
354 Shanghai(Zhou et al. 2024) were lower than Xiamen. This difference may reflect the winter-only design
355 of those studies, which also yielded broader NPETR ranges. Xiamen's NPETR was similar to that of
356 Chongqing(Qin et al. 2025), though slightly higher at upper and lower limits. Chongqing, which is
357 characterized by hot summers and cold winters, has an average maximum T_a (31.3°C) lower than Xiamen
358 (32.3°C).

359 Interestingly, neutral temperature ranges for Zhangjiakou(Li et al. 2025) and Xi'an(Ma et al. 2021)
360 —both in cold regions—were broader than Xiamen, with lower upper and lower limits. Notably, the
361 upper limit in Zhangjiakou was close to our finding. Study settings may explain this pattern. Unlike cold

region studies, our investigation was conducted in urban parks featuring dense vegetation and water features, which help lower T_a and T_g . These environmental conditions encourage diverse physical activities among the elderly, possibly resulting in a lower upper limit(Wang et al. 2023). In addition, activity intensity plays a significant role in thermal perception. An experimental study in Beijing reported outdoor thermal benchmarks under varying activity intensities and identified a narrow neutral temperature range(Li et al. 2026). The lower limit in Xiamen was below that of Beijing, despite comparable upper limits. Two methodological factors may account for this disparity. First, Beijing study was conducted only in summer, when thermal stress levels are typically higher. Second, our study relied on static observations and did not establish activity-specific thermal benchmarks.

In addition, neutral temperature range of the elderly in Xiamen was narrower than Lhasa(Yao et al. 2022)and Harbin(He et al. 2024), and the upper and lower limits were higher, which was mainly related to climatic background. Most elderly in these cold regions are better adapted to low temperatures, resulting in lower values in lower limit. Despite this cold adaptation, the upper limit in Lhasa was slightly higher than our result—likely due to the region's plateau climate, characterized by intense solar radiation and over 3,000 annual sunshine hours(Qin et al. 2025), which may raise the upper thermal threshold.

Preferred temperature

In this study, preferred temperature (25.5°C) was higher than NPET (23.5°C), indicating that the elderly tended to prefer warmer environments. This finding is consistent with previous studies reporting reduced thermal sensitivity in the elderly(Matzarakis et al. 2020; Lam et al. 2021). Similar conclusions have also been reported in indoor investigations, which demonstrated that the elderly require stronger thermal stimuli to elicit responses comparable to younger adults(Taylor et al. 1995). With advancing age,

deterioration in cardiovascular function and sweat gland activity may lead to attenuated thermoregulatory responses and prolonged recovery, thereby reinforcing preferences for warmer conditions.

TAR

TAR for the elderly was 7.2~21.45°C in Xiamen. TAR in Guangzhou was higher(Fang and Hu 2019), which may be attributable to the higher average T_a . Long-term exposure to hot environments may facilitate physiological regulation and promote adaptive behaviors, thereby enhancing thermal tolerance(Li et al. 2025).

TAR in Xiamen was narrower compared to HSCW regions, with both the upper and lower limits of TAR being lower. This discrepancy may be attributed to differences in climatic background, research period, survey population, and study setting(Ma et al. 2021; Wang et al. 2023; Li et al. 2026). Compared with other studies, our survey covered a longer period and capture a relatively moderate range of thermal conditions. During the investigation, observations were primarily conducted in open squares and shaded spaces where the elderly were most congregated. However, previous studies have reported that microclimatic variations may give rise to diverse thermal experiences and, consequently, increased thermal acceptability(Yin et al. 2021). Furthermore, our study was conducted in urban parks, which generally feature higher green coverage and more favorable environments compared with residential areas and nursing homes. We found the elderly were more willing to engage in activities when T_a and G were lower, which may explain the lower TAR in this study. Additionally, respondents in our study were the elderly aged 60 and above, whereas a comparative study in Shanghai focused on the elderly in nursing home(Zhou et al. 2024). The elderly in nursing home generally exhibit a high prevalence of chronic diseases. Previous studies have indicated that thermal benchmarks differ among the elderly with chronic

diseases, and that those with multimorbidity are more sensitive to cold environments(Li et al. 2025).

Influencing factors on thermal perceptions

Physical factors

Our results confirmed that physical factors, particularly T_a and T_g , were primary drivers of TSV.

This is in line with previous work underscoring the critical role of radiative and convective heat transfer

in thermal comfort(Yuan et al. 2023; Li et al. 2025). T_g showed stronger effects on thermal perception

than T_a , which agrees with Zhang et al.'s finding that the influence of T_a on TSV was significantly weaker

than that of T_g (Zhang et al. 2024). Although RH has been considered the least important factor in thermal

perception, our findings revealed a seasonal divergence: RH exerted negative effects in autumn and

winter, but positive effects in spring and summer. This seasonal pattern may be attributed to the

interaction between RH and T_a . Specifically, higher RH may exacerbate discomfort in cold environments,

while it may intensify feelings of stuffiness in hot environments(Lai et al. 2020). V_a showed no significant

effects on thermal perception across seasons in our study. This finding contrasts with a study conducted

in Dalian, which reported significant effects of V_a in a coastal park where respondents were more likely

to perceive sea breezes(Zhang et al. 2024).

Individual factors

Among individual characteristics, age and clothing insulation emerged as the most significant

factors influencing thermal perception. Due to age-related degeneration of central thermoregulatory

function, the elderly exhibit diminished thermoregulatory capacity and consequently reduced thermal

sensitivity. Our findings indicated that the elderly were less prone to perceive heat, which aligns with

previous studies(Ma et al. 2021) and further supports the hypothesis that aging attenuate thermal

sensitivity (Itani et al. 2020; Matzarakis et al. 2020). During winter, clothing insulation was found to significantly affect thermal perception. This is likely due to the elderly's behavioral tendency to increase clothing levels as a means of compensating for declines in thermal sensitivity. Supporting this view, Lai et al. reported that the elderly frequently adjust clothing to achieve thermal comfort (Lai et al. 2017). Additionally, gender differences were also noted in the literature, with previous studies indicating that females tend to be less tolerant of thermal stress than males (Lam et al. 2018; Yuan et al. 2023). Similarly, this study identified gender differences in thermal perception, with females exhibiting greater sensitivity to thermal environment. Activity levels also influenced thermal perception, in line with studies showing that individuals modulate activity for thermal comfort (Yuan et al. 2023).

Social factors

The influence of social factors on thermal perception was relatively limited, with the effect of companionship being particularly notable. In outdoor settings, individuals accompanied by others tend to exhibit greater tolerance to thermal stimuli (Aljawabra and Nikolopoulou 2018). Moreover, the presence of companions may divert attention from thermal discomfort. This finding suggests that social support enhances individuals' adaptability to thermal environment (Yuan et al. 2023). Monthly income significantly affected thermal perception, reflecting lifestyle differences across income groups. Higher-income groups reported more discomfort (Li et al. 2025), likely due to greater access to comfort resources and thus higher expectations (Aljawabra and Nikolopoulou 2018).

Psychological factors

In this study, thermal perception was significantly influenced by LoR and DoE. LoR refers to an individual's psychological adaptation to thermal environment. The longer a person resides in a given

climate, the greater degree of acclimatization to that environment(Zhang et al. 2024). DoE is associated with the psychological concept of "*alliesthesia*", whereby increase in DoE may weaken response to thermal stimuli(Krüger et al. 2015). This suggests that as DoE increases, the ability to adapt to outdoor environments gradually improves(Zhang et al. 2024). Furthermore, FoA also affected thermal perception in winter, suggesting that frequent outdoor attendance may facilitate gradual acclimatization to local climate. A study in Xi'an reported that thermal comfort and acceptability among urban and rural residents increased with overall satisfaction(Yuan et al. 2023). This aligned with our findings, which identified SaS as a significant factor affecting thermal perception. Previous studies also indicated that thermal perception is influenced by PoA(Yuan et al. 2023; Zhang et al. 2024). In this study, only the elderly who engaged in "exercise" demonstrated higher thermal acceptability in winter.

Behavioral adjustments

The elderly exhibited a clear preference for engaging in activities during periods of greater thermal comfort. The mild autumn climate permitted a wider distribution of activities. In hot and humid regions, attendance has been found to be negatively correlated with PET(Li et al. 2024), a pattern consistent with our observations. In spring and autumn, a quadratic relationship was observed between attendance and PET, suggesting that the willingness to participate in activities is largely governed by thermal comfort(Li et al. 2024).

Behavioral adaptation serves as a key mechanism for enhancing OTC. The most prevalent coping strategies were "moving into sunlight" and "moving to shaded areas". Lai et al. found each unit increase in TSV corresponded to a 26% reduction in sun-exposed individuals and a 27% increase in those occupying shaded locations(Lai et al. 2020). The general preference for shade-seeking behavior in

outdoor environments further emphasizes the importance of spatial heterogeneity within urban parks in supporting thermal self-regulation(Zhang et al. 2019). Clothing adjustment played a secondary role in our study, possibly because the openness of urban park limits the feasibility of clothing choices. "Drinking water" was another important strategy for alleviating thermal discomfort. Accordingly, installation of drinking water facilities in urban parks may effectively enhance outdoor experience. Adjusting exercise intensity was also recognized as a measure for improving OTC. Questionnaire responses revealed that the elderly preferred to increase exercise intensity to meet thermal demand in winter, rather than simply adding more clothing. This finding corroborates previous studies, which suggested that adjusting activity intensity in response to thermal conditions is an effective behavioral strategy(Wang et al. 2023). These behavioral responses indicate that the elderly are not passive recipients of the thermal environment, but rather agents who adopt adaptive strategies to maintain comfort. Therefore, urban parks should be designed and managed to facilitate such adaptive behaviors.

Limitations

In this study, several limitations need to be acknowledged: (1) Thermal perception was assessed only under static conditions, limiting understanding of its variability in dynamic environments and activities. (2) Heterogeneous nature of the elderly sample precluded a detailed analysis of individual-level determinants. (3) The lack of physiological data prevents a full understanding of the biological processes that underlie thermal adaptation in the elderly. Further research should consider multimodal effects of environmental factors (such as acoustic environment, olfactory stimuli) on thermal perception. Experimental designs should also integrate physiological measurements with subjective evaluations to provide a more comprehensive assessment. Such efforts would deepen understanding of thermal

demands and offer valuable guidance for the age-friendly design of urban parks.

Conclusions

This study evaluated OTC of the elderly in HSWW regions. Based on field measurements and questionnaire surveys, we systematically analyzed three key aspects: thermal comfort thresholds, factors affecting thermal perception, and activity characteristics. The main conclusions are drawn as follows:

(1) The largest proportions of TSV were "neutral" and "slightly hot", and proportion of respondents feeling uncomfortable was slightly higher than those reporting comfort. TSV was strongly correlated with TCV, with peak comfort at $TSV = -0.14$.

(2) NPET for the elderly was 23.5°C , with NPETR of $19.01\text{--}27.98^{\circ}\text{C}$. Preferred PET was 25.5°C and 80% of the elderly exhibited a TAR of $7.2\text{--}21.45^{\circ}\text{C}$. When MTSV ranged from -1 to +1, PPD was lower than ISO 7730 standard, indicating that the elderly are satisfied with outdoor environment when its comfort level was comparable to indoor environment.

3) In winter, thermal perception was affected by physical (T_g and RH), individual (age and clothing thermal resistance), social (companionship), and psychological factors (FoA, SaS, and PoA). In spring, the determinants included physical (T_a , RH , and T_g), individual (age and gender), social (companionship and monthly income), and psychological factors (SaS). In summer, thermal perception was affected by physical (T_a , RH , and T_g), individual (gender and age), social (companionship and monthly income), and psychological factors (SaS). In autumn, the influencing factors comprised physical (T_a , RH , and T_g), individual (age and activity level), social (monthly income), and psychological factors (LoR, DoE, and SaS). Overall, mathematical model between TSV and influencing factors performed well, with physical factors exerting the greatest influence on TSV.

4) In spring and autumn, PET and attendance exhibited a quadratic relationship, with attendance peaking when PET approached neutral temperature. In summer, attendance was negatively correlated with PET, and remained minimal when PET exceeded 37°C. Thermal adaptation behaviors showed distinct seasonal variations, with the elderly primarily satisfying thermal needs by regulating thermal radiation.

This study aims to investigate OTC of the elderly in HSWW regions, contributing to filling a gap in current knowledge. The findings provide empirical evidence for urban designers, thereby supporting the design of age-friendly environments and contributing to the development of age-friendly cities.

Author contributions

Z.Z.: Conceptualization, Methodology, Data curation, Investigation, Visualization, Writing-original draft, Writing-review & editing, Formal Analysis, Software, Validation; L.D.: Resources, Funding Acquisition, Supervision, Project administration.

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Data availability

The data used in this study is available upon reasonable request made to the corresponding author.

Declarations

Ethical standard and consent to participate The experiments comply with the current laws of the country in which they were performed. Informed consent was obtained from all individual participants included in the study.

Ethics approval The study was conducted using anonymized data, without involving sensitive personal

information or commercial interests, and posed no harm to the participants. Therefore, our study received an ethics approval waiver from the department. And the procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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