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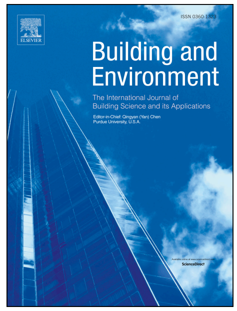

Relationships between EEG and thermal comfort of elderly adults in outdoor open spaces

Xiaoyan Ma, Lin Song, Bo Hong, Yichen Li, Yang Li

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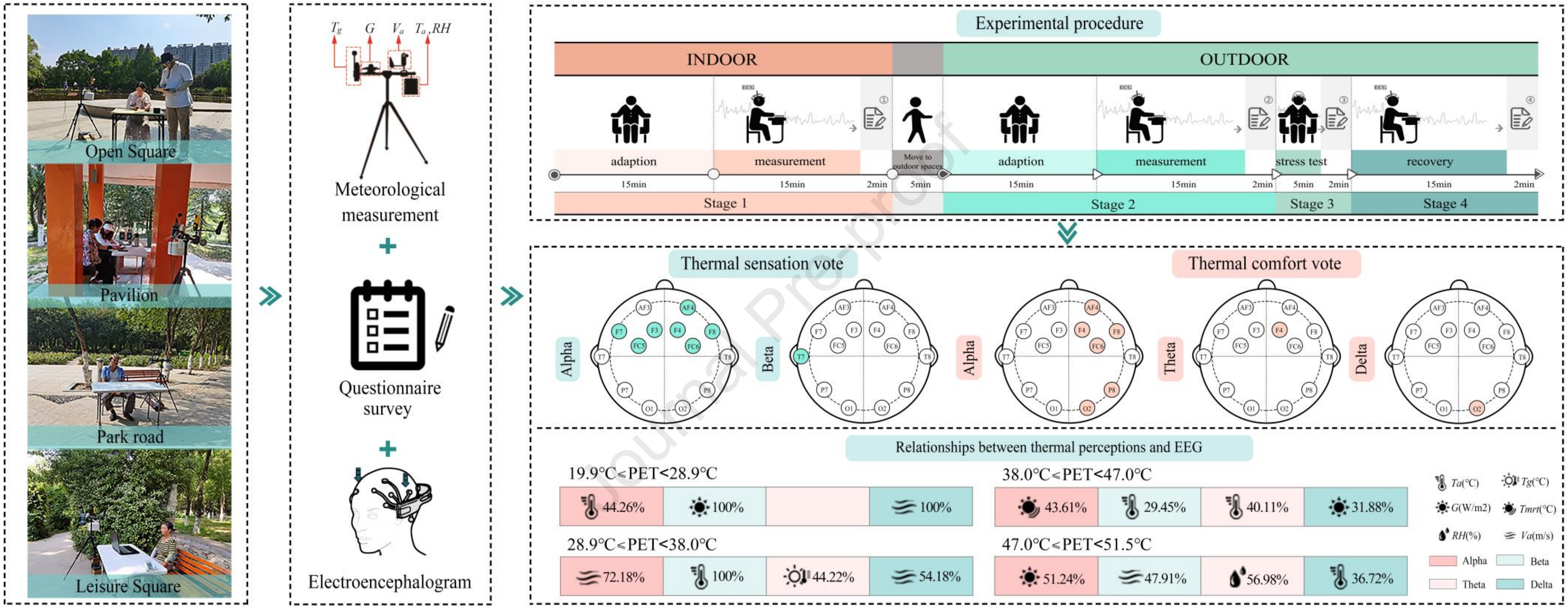

Open Square
Pavilion
Park road
Leisure Square
T_g G V_a T_a,RH
Meteorological measurement
Questionnaire survey
Electroencephalogram
Experimental procedure
INDOOR
OUTDOOR
adaption
measurement
Move to outdoor spaces
adaption
measurement
stress test
recovery
15min
15min
2min
5min
15min
15min
2min
5min
2min
15min
2min
Stage 1
Stage 2
Stage 3
Stage 4
Thermal sensation vote
Thermal comfort vote
Alpha
Beta
Alpha
Theta
Delta
Relationships between thermal perceptions and EEG
19.9°C<PET<28.9°C
44.26%
100%
100%
28.9°C<PET<38.0°C
72.18%
100%
44.22%
54.18%
38.0°C<PET<47.0°C
43.61%
29.45%
40.11%
31.88%
47.0°C<PET<51.5°C
51.24%
47.91%
56.98%
36.72%
Ta(°C)
Tg(°C)
G(W/m2)
Tmrt(°C)
RH(%)
Va(m/s)
Alpha
Beta
Theta
Delta

Title: Relationships between EEG and thermal comfort of elderly adults in outdoor open spaces

Authors: Xiaoyan Ma[#], Lin Song[#], Bo Hong*, Yichen Li, Yang Li

Affiliation:

College of Landscape Architecture & Arts, Northwest A&F University, Yangling 712100, China

***Corresponding author.** hongbo@nwsuaf.edu.cn/ hongbo@nwafu.edu.cn (B. Hong).

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[#]These authors contributed equally to this work.

Relationships between EEG and thermal comfort of elderly adults in outdoor open spaces

Abstract: We investigated the relationship between variation in EEG signal characteristics (α, β, θ and δ frequency bands) of elderly adults and their thermal perceptions in outdoor environments in Xi'an, China using meteorological measurement, subjective questionnaire survey and EEG signal monitoring. We found that: 1) the δ, θ and β relative powers of the frontal lobe were significantly correlated with physiological equivalent temperature (PET), globe temperature (T_g), wind speed (V_a), mean radiant temperature (T_{mrt}) and global radiation (G). The α, δ and β relative powers of parietal lobe were significantly correlated with PET, T_g, air temperature (T_a) and relative humidity (RH). 2) The α relative power of the frontal lobe varied with an inverted U-shape with an increase in thermal sensation. The α wave of the frontal lobe was the most accurate index to evaluate elderly adults' thermal sensation. 3) The α wave of the right cerebral hemisphere can be used to identify elderly adults' thermal comfort, particularly the O2 channel of the occipital lobe. 4) T_a and V_a were dominant influences of the EEG among elderly adults. The meteorological factors that affected the EEG changed as thermal stress fluctuated; most meteorological factors were positively related to thermal stress. Our results provide theoretical evidence of the predictive accuracy of outdoor thermal comfort models for elderly adults and contribute to the practical bioclimatic design of outdoor open spaces for vulnerable groups.

Keywords: Outdoor thermal comfort; Elderly; Electroencephalogram (EEG); Physiological equivalent temperature (PET); Meteorological parameters; China's cold region

Nomenclature

EEG	Electroencephalogram	TCV	Thermal comfort vote
PET	Physiological Equivalent Temperature	TSV	Thermal sensation vote
T_g	Globe temperature	SVF	Sky view factor

V_a	Wind speed	OS	Open square
T_{mrt}	Mean radiant temperature	PV	Pavilion
G	Global radiation	PR	Park road
RH	Relative humidity	LS	Leisure square
BP	Blood pressure	IS	Indoor space
HR	Heart rate	ICA	Independent component analysis
SpO_2	Oxyhemoglobin saturation	MTSV	Mean thermal sensation vote
~~ECG~~	Electrocardiograph	VIF	Variance inflation factor

1. Introduction

The percentage of Chinese residents over 60 years old reached 18.7 of the total population in 2022. This number is expected to exceed 30% by 2040 [1,2]. The growing population of elderly adults is an important user group of urban open spaces [3], and research has shown that high-quality spaces can attract more elderly adults to participate in outdoor activities [4]. These factors are conducive to improving the physical and psychological health and happiness for aging adults [4]. Among factors influencing quality of urban open spaces, thermal comfort is considered one of the most important [5].

Studies of thermal comfort in elderly adults are principally based on physiological characteristics that are correlated to an individual's cold and thermal sensation [6,7]. With age, physiological characteristics of adults changed, i.e., the decreased sensitivity of vasoconstriction (or angiectasis) decreases sweating and increases body fat accumulation and may contribute to weaker thermoregulation, resulting in significant differences between elderly adults and other groups in outdoor recreational patterns [8,9]. Moreover, the elderly may not be able to accurately and objectively evaluate the thermal environment due to decreased cognitive ability and changes in psychological states (e.g., emotional responses to environments). These factors intensify their thermal health risks [10–12].

Physiological parameters, such as blood pressure (BP), heart rate (HR), oxyhemoglobin saturation (SpO2), skin temperature (ST) and sweat feeling index, can be used as objective measures reflecting human thermal comfort [13–15]. HR and SpO2 are significantly correlated with human thermal comfort vote (TCV) [16]. Under cold and mild conditions, there is a strong correlation between mean ST and thermal sensation [13], but these indices have a characteristic lag time for elderly respondents. Since common drugs for chronic diseases in elderly adults may delay responses to physiological indices like BP, HR or sweat rate, it is challenging to identify immediate responses of thermal sensation to climate conditions among elderly adults, affecting our ability to identify environmental threats to their health [17,18].

The electroencephalogram (EEG) measures electrical signal changes in the brain when cerebral cortex perceives and recognizes environmental information. It can predict physiological and psychological change [19]. As a quantitative index to measure thermal comfort, EEG has attracted much attention in recent years. Deboer et al. reported that EEG frequency changes were parallel to changes in body or brain temperature and influenced the EEG power density spectrum [20]. Thermal signals from the skin can arrive rapidly and simultaneously at several regions of cerebral cortex [21]. Hence, the EEG is generated quickly, realizing real time monitoring. Compared with existing physiological information types such as ST or electrocardiogram (ECG), EEG can immediately reflect changes in human thermal sensations [22].

Existing studies of thermal perception and EEG have focused on analyzing changes in EEG frequency bands. Yao et al. collected subjects' thermal sensation vote (TSV) at four temperatures (21, 24, 26, and 29°C) to test the EEG. They demonstrated that the β relative powers at 21 and 29°C were significantly higher compared to those at 24 and 26°C [23]. When people perceive thermal discomfort as gradual temperature increases or decreases, the α, β, θ and δ relative powers all increase significantly [24]. Lan et al. found that the δ relative power increased significantly with a neutral thermal sensation, while β and α relative powers increased significantly at indoor temperatures of 17 and 28°C [25]. Son et al. reported that an individual's thermal pleasure was positively related with the θ relative power of at the Fz, Cz and POz channels [26]; the α/β relative power was significantly correlated with thermal satisfaction within the temperature difference range of a heated seat [27].

In addition to air temperature (T_a), changes in relative humidity (*RH*), wind speed (V_a) and radiative temperature may influence EEG. Pan et al. simulated three airflow condition levels (0, 0.5, and 1.0 m/s) in the laboratory to determine how airflow affected the EEG signal. They found that, compared to 0.5 and 1.0 m/s, the relative β and δ powers of the F3 channel increased significantly without airflow (0 m/s) [28]. With an increase in radiative temperature, the β and α relative powers increase along with increasing EEG asymmetry of the frontal lobe, creating in the inverted "U" shape response curve [29]. When the *RH* is 70%, the δ relative power increases significantly as T_a increases, whereas α, β and θ relative powers decline significantly [30]. This demonstrated that EEG can be used to understand mechanisms of thermal comfort, permitting an objective and instantaneous measure of the effects of environment on perception.

Nevertheless, existing studies of the relationships between thermal comfort and EEG are mainly conducted during indoor steady-state trials and typically explore influences of single environmental factors (T_a or *RH*) on EEG. In less controlled outdoor environments, EEG changes among elderly adults are likely sensitive to comprehensive effects of multiple meteorological factors. However, there are few studies measuring EEG characteristics of elderly adults in variable outdoor environments. Therefore, quantifying the relationships between thermal perception and EEG of elderly adults is vital to those who cannot make objective evaluations of their own thermal comfort. Judging thermal discomfort among elderly adults by real-time monitoring of their EEG changes and using this to improve environmental factors that cause thermal discomfort can improve their experience of outdoor open spaces and thus quality of life.

In our study, outdoor open spaces typical for Xi'an, China were chosen to investigate the relationships between thermal comfort and EEG of elderly adults. We compared meteorological conditions to a subjective questionnaire survey and EEG signal monitoring (α, β, θ and δ frequency bands). The primary aims of our study were to: 1) analyze the relationship between outdoor meteorological variables and EEG readings from elderly adults to determine the influencing mechanisms of meteorological parameters on EEG signals, 2) link EEG variation among elderly adults relative to different thermal perceptions and identify the specific brain regions and frequency bands of EEG that can reflect elderly adults' thermal perception, and 3) explore outdoor meteorological parameters that influence EEG variation among elderly adults as well as the influencing weight of each parameter. Our results are intended to provide a theoretical evidence to accurately evaluate thermal comfort of elderly adults using EEG readings and propose bioclimatic designs of outdoor open spaces for older urban residents.

2. Methods

2.1. Study sites

Xi'an is located at the intersection of semi-arid and humid subtropical climate zones, belonging to the semi-humid continental monsoon region of the warm temperate zone [31]. Climate data from 2011 to 2021 show that the highest annual T_a occur in July and August with a maximum average T_a of 27.2℃. The highest average T_a reaches 38.1℃. The average RH in summer varies between 60.6 and 74.4% [32].

Field trials were conducted in an urban park (34°13′5″N, 108°57′51″E) in Xi'an. The park contains abundant types of both open spaces and activity facilities, attracting elderly adults for exercise and entertainment. Four typical spaces were chosen based on the recorded attendance of elderly adults, spatial element composition, and sky view factor (SVF), including an open square (OS), pavilion (PV), park road (PR) and leisure square (LS) (Fig.1).

Based on previous research [33], T_a in outdoor open spaces is influenced by the surrounding environment within the central radius of 10–150 m. Therefore, the landscape element composition of spaces was measured within a 10 m radius of measured point centers (314 m^2). Fisheye photos at each measured point were taken and input into Rayman software to calculate SVF (Table 1).

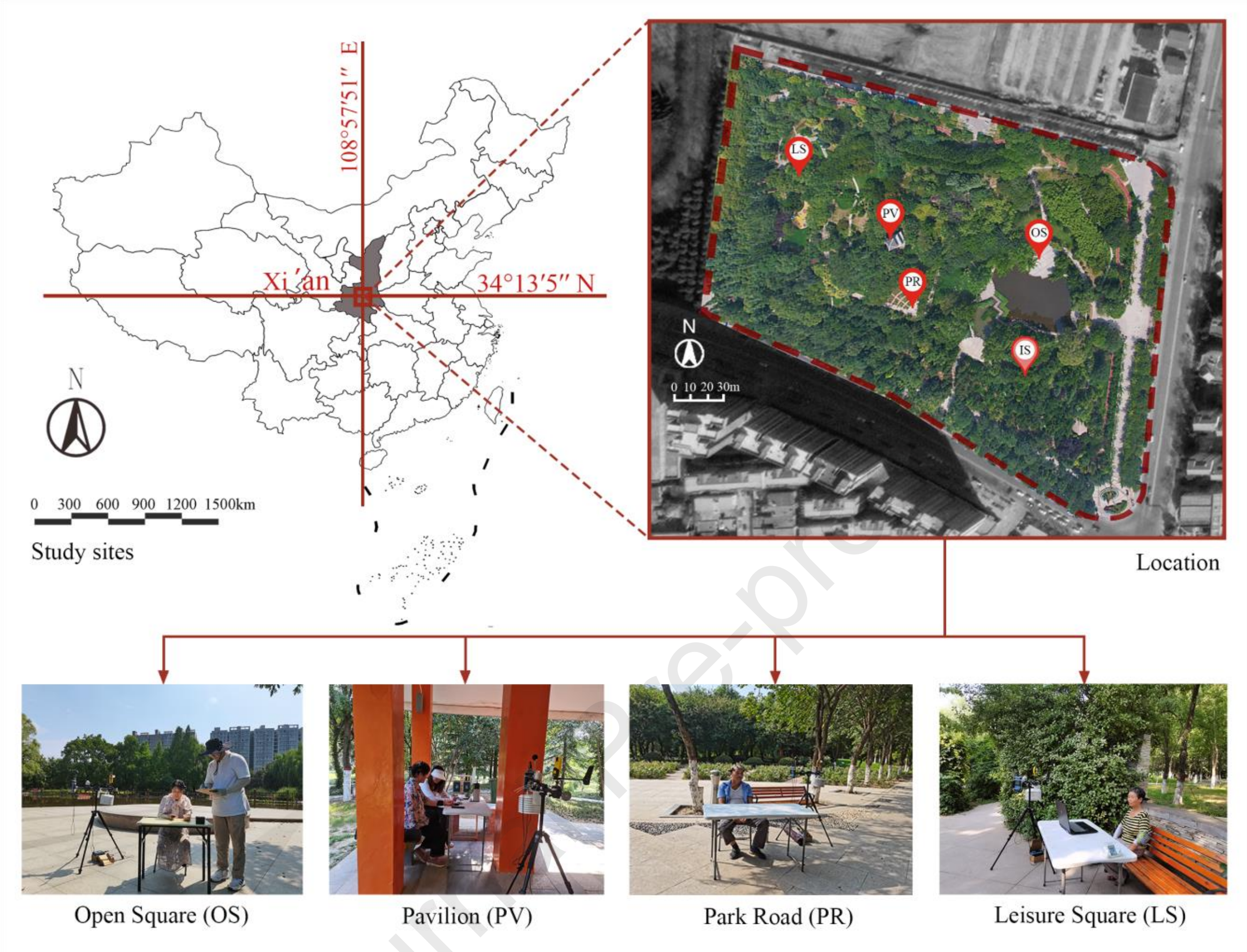
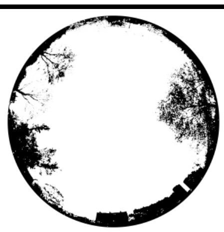
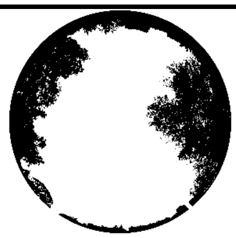
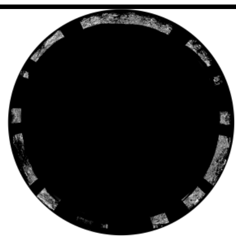
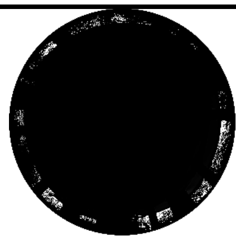
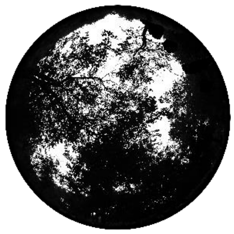


Fig.1. Site locations and measured spaces (baseline measurement in indoor space (IS)).

Table 1. Descriptions of the four open spaces.

Site	Characteristics	Spring	Summer
OS	An open square next to a lake. The main landscape elements consist of granite pavement (62%), vegetation (13%) and artificial lake (25%).	 SVF = 0.79	 SVF = 0.63

PV	Landscape pavilion. It is composed of granite pavement (37%) and vegetation (63%).	 SVF = 0.04	 SVF = 0.01
PR	Main park road. It contains permeable brick paving (42%), tree pools (15%), and flower pond (43%). The measurement site is adjacent to the road.	 SVF = 0.34	 SVF = 0.29
LS	Leisure square. Enclosed by a landscape wall, its landscape elements consist of granite pavement (36%), flower bed (18%) and trees (46%).	 SVF = 0.42	 SVF = 0.30

2.2. Measurements

Experiments were conducted on sunny and windless days in spring (April 8–10, 2022) and summer (August 1–3, 2022) representing seasonal weather for this time of year in Xi'an, China.

2.2.1. Meteorological measures

A meteorological monitoring station was sited at each trial location, installed 1.1 m above the ground. All meteorological parameters were recorded at one-minute interval, including T_a, RH, V_a, globe temperature (T_g) and global radiation (G). T_a and RH were recorded by the HOBO onset U23-001 (ONSET, USA) that was fixed into a solar radiation shield. T_g was measured using a black globe thermometer (Delta OHM HD2107.2, Italy), and G using a solar radiation automatic recorder (Delta OHM HD2102.2, Italy). V_a was collected using a portable anemometer (Kestrel 5500, Nielsen-Kellerman Co. USA). The mean radiant temperature (T_{mrt}) was calculated using T_a, T_g and V_a [34] (*Appendix Table A*).

$$T_{mrt}=[\left(T_g+273\right)^4+\frac{1.10*10^8 V_a^{0.6}}{\varepsilon D^{0.4}}\left(T_g\text{-}T_a\right)]^{\frac{1}{4}}\text{-}273 \tag{1}$$

where D is the globe diameter (D=0.05 m) and $\mathcal{E}$ is the emissivity ($\mathcal{E}$=0.95 for a black globe).

2.2.2. Questionnaire

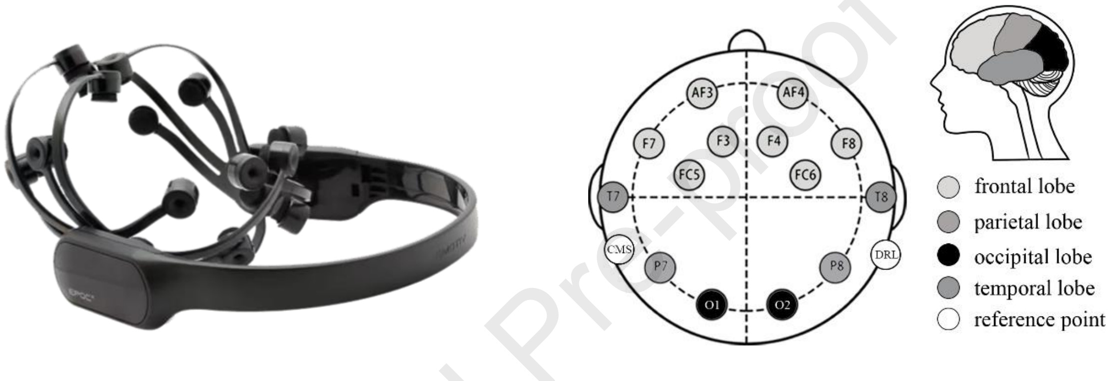
The questionnaire survey was completed simultaneously with meteorological measurements. Part I of the questionnaire collected basic personal information, including gender, age, height, weight, clothing and residence time. Part II investigated elderly adults' thermal perception, including thermal sensation and thermal comfort. TSV used the Likert-7 scale (cold (−3); cool (−2); slightly cool (−1); neutral (0); slightly warm (+1); warm (+2); hot (+3)) [35]. TCV was evaluated on a three-level scale (uncomfortable (−1); moderate (0); comfortable (+1)) (*Appendix Fig. A*).

Since some questions were difficult to distinguish from one another and the elderly adults may not be able to fully understand the content, researchers described the meaning of questions to help with understanding and response accuracy. We collected 288 questionnaires of which 280 were valid.

2.2.3. EEG

EEGs were measured using an Emotiv EPOCx (EMOTIV Inc. USA). Emotiv EPOCx has 14 EEG measurement channels and 2 reference channels (CMS and DRL). It provides accurate spatial resolution and positioning, and records deep information of cerebral activity. We referenced the international 10-20 system, mapping 14 channels located at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF4 [36]. These are located in four major regions of the brain: frontal lobe (AF3, F7, F3, FC5, FC6, F4, F8 and AF4), temporal lobe (T7, T8), occipital lobe (O1, O2), and parietal lobe (P7, P8). The sampling frequency of the EPOCx is 128Hz (once sample each 0.0078s). With assistance, EPOCx was worn on the respondents' heads, and all felt sensor pads were wetted with saline solution to assure appropriate electrical conductivity through the scalp. Respondents were asked to sit comfortably and upright to ensure effective contact between all electrodes and scalp. The measured signals of EPOCx were recorded by Emotiv PRO software that made real-time check and storage of sensor data (Fig.2).

The relative powers of the four frequency bands were used to quantify cerebral activity, including δ (1–3Hz), θ (4–7Hz), α (8–13Hz), and β (14–30Hz). In general, the δ wave is primarily associated with sleepiness [37], and the θ wave is related to positive emotional or blissful positive states during meditation [38,39]. The α wave is the most prominent rhythm of brain activity and is generated when a person is relaxed, calm and stable [40]. Finally, the β wave is the usual waking rhythm of the brain associated with active thinking, active attention, focused on the outside world or solving concrete problems [37].



(a) (b)

Fig.2. Measurements of EEG signals: EEG acquisition with EPOCx headset (a), and electrodes on the scalp (b).

2.3. Experimental design

2.3.1. Experimental procedure

Before trials, information about the anticipated experiment duration, ability to understand the questionnaire, acceptable stress range, and stress application mode was communicated to the participants. With this information, the specific experimental procedure was determined. The experiments were conducted during daytime hours (9:30–11:30 and 14:00–17:30) when many elderly adults were out for activities and recreation. Four respondents started the experiment simultaneously, with each respondent spending approximately 93 min to complete four trial stages (Fig.3).

Stage1: Respondents were in the indoor space for baseline measurements. Researchers described the basic process and intentions and then the experiment officially started. Respondents were given

15 min of thermal adaptation time indoors to achieve a steady state. After this adaptation period, respondents were randomly assigned to one of the four experimental spaces and 15 min of EEG records were conducted. Subsequently, respondents were asked to complete the first questionnaire.

Stage 2: Respondents were given 15 min to adapt thermally to the outdoor experimental spaces, followed by 15 min of EEG recording. Respondents then completed the second questionnaire.

Stage 3: A stressful task was performed during this stage to vary the thermal perception of elderly adults. The task included 5 min of solving as many two-digit addition and subtraction problems as possible while noises were played. The audio was played by researchers according to the acceptability of elderly adults. To avoid interference from the surrounding environment, respondents were asked to wear headsets during the trial. After finishing the stressful task, respondents filled in the third questionnaire. We confirmed whether the task changed the thermal perception of elderly adults using a comparison of questionnaire survey results before and after the stressful task.

Stage 4: Respondents continued to recover for 15 min in experimental spaces and EEG signals in this stage were recorded. Subsequently, respondents filled in the fourth questionnaire.

The Emotiv EPOCx measures EEG responses in real time. Respondents wore Emotiv EPOCx on their heads for each stage. To assure stability and accuracy of recording, respondents were asked to sit quietly throughout the experiment. To eliminate interference from other anthropic factors on EEG and thermal comfort of elderly adults, researchers kept other visitors from the experimental spaces during trials. To avoid the EEG signal changes caused by filling in the questionnaires, the questionnaire survey was conducted after the EEG was recorded at each experimental stage.

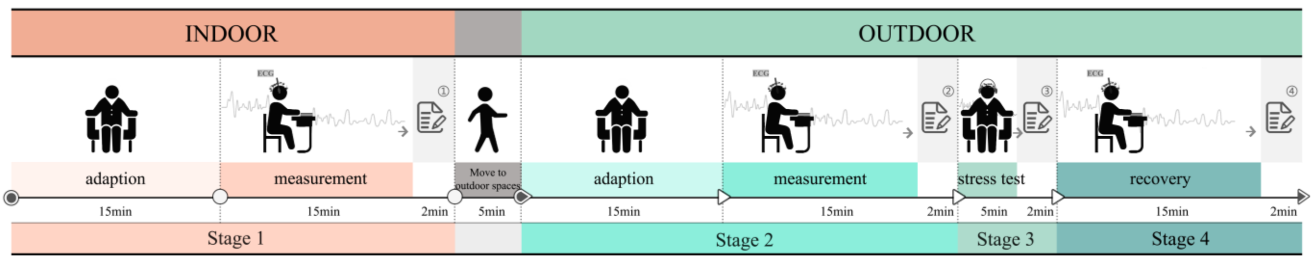


Fig.3. Experimental procedure.

2.3.2. Volunteer selection

Elderly adults over 60 years old who had lived in the local area for more than one year were recruited. The cognitive ability of elderly adults declines gradually with age, accompanied by impaired vision and hearing loss. Because these factors could affect research conclusions, we recruited volunteers in advance to meet the following requirements: 1) Unimpaired hearing, vision and cognitive ability; 2) ability to solve two-digit addition and subduction problems, and 3) clear understanding of the questionnaire. All volunteers were right-handed and in good health. They had no history of neuropsychiatric disorders, such as cerebral trauma, epilepsy, attention deficit disorder, and did not engage in any addictive behaviors such as alcoholism or smoking. Before participating in the trial, volunteers were asked to get enough sleep and eat a healthy diet. They were forbidden to take drugs that had an impact on the experiment or drink tea, alcohol, coffee or other stimulating beverages 24 hours before the experiment. To ensure satisfactory signal monitoring from the EEG measuring equipment, volunteers were asked to keep their scalp clean (*Appendix Table B*).

2.4. Data analysis

The raw EEG data were preprocessed using the EEGLAB tool kit (version14.0.0) run in Matlab, including packages "removing artifacts" and "filtering frequencies". Filters eliminate brain waves below 1Hz and above 30Hz. Artifacts like blinking and muscle activities were eliminated in the independent component analysis (ICA) algorithm in EEGLAB. EEG contaminated by artifacts were input into ICA to separated EEG from artifacts. The functional processing of "artifact-free" EEG data was conducted using Matlab to determine the relative powers of δ, θ, α, and β. This process was conducted on all 14 EEG channels, thus determining the relative powers of four frequency bands in the four experimental spaces for subsequent statistical analysis.

We used physiological equivalent temperature (PET) to predict thermal comfort of elderly adults. Meteorological parameters (T_a, RH, V_a, T_{mrt}, and G) and personal data (height, weight, age, gender, clothing insulation, and metabolic rate) were input into the RayMan model to calculate PET value of elderly adults during trials.

All statistical methods were performed in SPSS 26. Meteorological parameters among experimental spaces and EEG signals under different thermal perceptions were analyzed by one-way analysis of variance (ANOVA). The correlation between EEG and meteorological parameters among cerebral cortex regions was analyzed using a Pearson correlation. Meteorological factors that influence EEGs of elderly adults and influencing weights under different thermal stress levels were analyzed with multiple linear stepwise regression.

3. Results

3.1. Meteorological parameters

Meteorological variables in each measured space were aggregated every 0.5h. Significant differences of meteorological variables among the four spaces were determined through a post-hoc Tukey's test (Table 2; *Appendix Fig. B*).

The local climate is mild in spring, and differences in thermal environment characteristics of each measured site were small. Space OS had the highest T_a, T_g, G and T_{mrt}, while PV had the lowest. RH in all spaces was relatively low, but V_a was relatively high. The mean RH in space OS was the lowest, but its mean V_a was the highest. In summer, space OS was exposed to direct sunlight throughout the day, so T_a, T_g, G and T_{mrt} were highest here. Due to a wind corridor formed by abundant vegetation and surrounding buildings at space OS, V_a was high. Although space OS was close to the lake, it had the lowest RH due to the high V_a, which accelerated the evaporation of water from this space. Space PV was in the shade of a building during the daytime, creating large differences with space OS that was unshaded. At space PV, T_a, T_g, G, and T_{mrt} were the lowest. Since space PV was surrounded by vegetation, RH was high due to plant transpiration. Space PR was adjacent to the main park road and was relatively open. Although there was high SVF in space PR, it still received solar radiation for a long period during the day. Hence, T_a, T_g, G and T_{mrt} were high. Space LS was in plant shade throughout the day, resulting in the low T_g and G.

248 **Table 2.** Meteorological variables among spaces.

	Variable		OS	PV	PR	LS
Spring	T_a (°C)	Max	33.2	31.1	31.9	31.7
		Mean±SD	25.5±3.75	24.2±3.62	24.5±3.80	24.5±3.76
		Min	17.8	17.1	17.1	17.2
	T_g (°C)	Max	47.4	31.8	44.3	46.7
		Mean±SD	36.8±4.06	24.7±3.33	32.1±5.01	33.2±4.70
		Min	26.2	17.6	19.8	19.6
	RH (%)	Max	52.6	58.1	55.0	55.4
		Mean±SD	34.1±7.18	38.8±7.50	36.6±7.36	37.6±7.61
		Min	15.7	19.4	18.2	9.8
	V_a (m/s)	Max	3.3	2.2	2.6	2.2
		Mean±SD	1.7±0.26	1.1±0.20	1.3±0.21	1.1±0.10
		Min	0.0	0.0	0.0	0.0
	G (W/m^2)	Max	866.0	43.0	941.0	811.0
		Mean±SD	395.4±242.56	17.9±7.30	240.8±239.64	199.5±130.38
		Min	5.0	0.0	32.0	6.0
	T_{mrt} (°C)	Max	94.4	35.8	79.9	84.8
		Mean±SD	60.5±10.47	26.7±3.30	49.8±8.77	52.3±5.83
		Min	26.7	17.6	19.8	19.5
Summer	T_a (°C)	Max	36.7	35.0	35.7	35.1
		Mean±SD	33.6±1.91	32.3±1.96	32.8±2.05	32.3±1.96
		Min	28.7	27.6	28.0	27.8
	T_g (°C)	Max	51.0	35.6	48.3	45.0
		Mean±SD	42.8±3.00	33.1±1.81	39.7±4.26	34.7±2.45
		Min	35.1	28.5	29.8	29.1
	RH (%)	Max	68.8	73.5	73.5	73.4
		Mean±SD	56.6±4.85	62.6±5.26	60.4±5.58	62.1±4.97
		Min	46.5	51.8	50.4	51.4
	V_a (m/s)	Max	3.20	2.40	2.60	2.70
		Mean±SD	0.44±0.14	0.14±0.14	0.49±0.16	0.10±0.06
		Min	0.00	0.00	0.00	0.00
	G (W/m^2)	Max	953.6	46.9	862.5	647.9
		Mean±SD	513.0±241.91	18.2±10.12	402.7±238.39	91.8±63.77
		Min	72.6	0.4	57.2	27.4
	T_{mrt} (°C)	Max	107.3	40.3	91.6	71.0
		Mean±SD	54.1±9.06	33.6±2.11	50.1±10.02	35.6±3.09

	Min	35.1	28.5	29.8	29.1

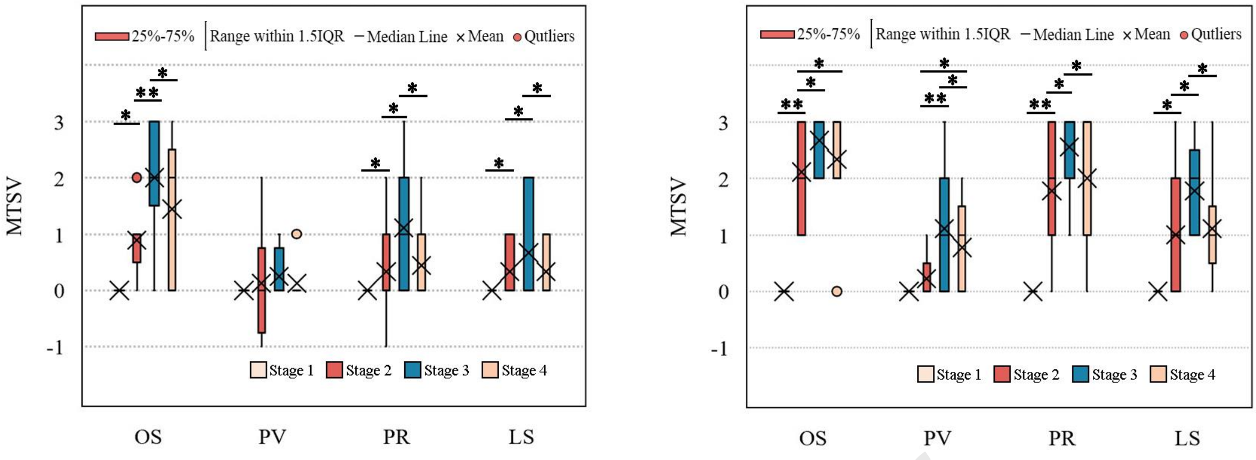
*SD represents standard deviation.

3.2. Thermal perceptions

3.2.1. TSV

In spring, elderly adults were studied in controlled indoor spaces during stage 1 where TSV distributed as “neutral”. After a move to outdoor spaces (stage 2), TSV increased the most significantly in OS (p<0.01). This was because high T_a and radiation greatly influenced thermal sensation of elderly adults. In stage 3, the TSV in all spaces changed after they completed the stressful task. TSV increased significantly in spaces OS, PR and LS (p<0.05). Although TSV increased to some extent in space PV, this difference was insignificant. Compared to stage 3, TSV generally had a decreasing trend in stage 4. Spatially, TSV declined significantly in trial sites OS, PR and LS (p<0.05).

In summer, observed TSV changes among elderly adults in trial spaces were more significant compared to those in spring. External environmental stimuli appeared to influence thermal sensation of elderly adults greatly due to the hot summer environment. Similar to spring trials, TSV in stage 1 distributed in the “neutral” range. In stage 2, TSV increased significantly in spaces OS, PR and LS (p<0.01), but did not change significantly in space PV. This was because it was shaded by a building and had a cooler thermal environment. After the stressful task, TSV in four spaces increased significantly (p<0.05). This demonstrated that elderly adults’ thermal sensation was influenced by not only the thermal environment, but also psychological factors (e.g., stress). In stage 4, TSV decreased significantly in spaces PV, PR and LS (p<0.05), but not in space OS (Fig.4).



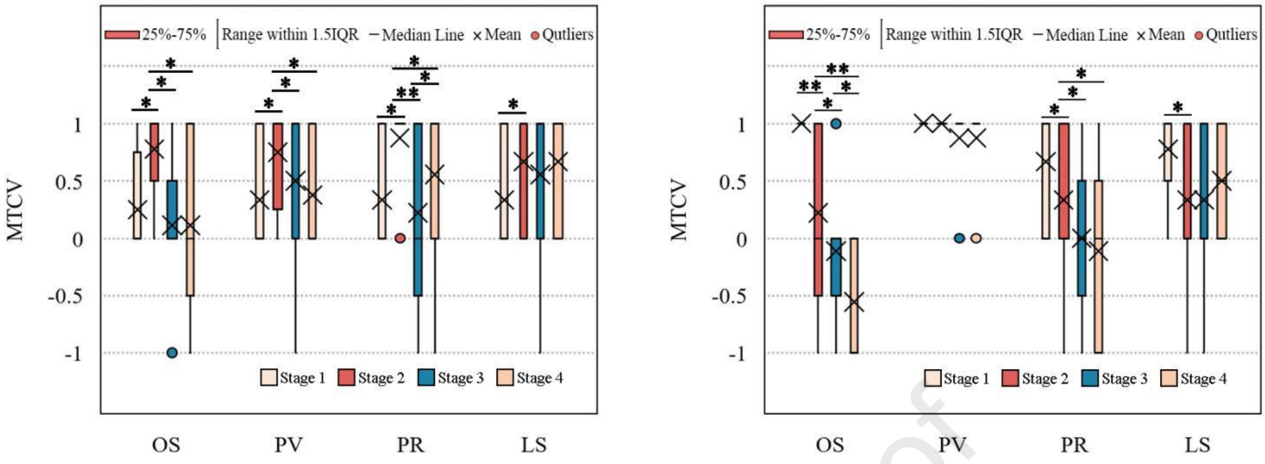
(a) (b)

Fig.4. Thermal sensation vote across all four stages as defined in the text: spring (a) and summer (b) (* <0.05; ** <0.01).

3.2.2. TCV

In spring, the TCV of elderly adults in stage 1 was predominantly distributed in the "neutral" zone but increased significantly after moving to outdoor spaces (stage 2). This was because the outdoor thermal environment in spring was mild and elderly adults felt relatively comfortable in outdoor spaces. During stage 3, TCV decreased significantly in OS, PV and PR (p<0.05). The stressful task also clearly changed thermal comfort level. After 15 min of recovery (stage4), TCV increased significantly in PR (p<0.05) but showed clear differences to other spaces. Changes in LS were not significant in stages 2, 3 and 4. This suggests that stressful tasks had no influence on thermal comfort of elderly adults in space LS, which might be related with the favorable thermal environment and spatial characteristics, such as abundant vegetation.

In summer, TCV values in stage 1 were primarily distributed in the "comfortable" zone. After moving to outdoor spaces, thermal comfort decreased significantly in spaces OS and PR (p<0.05). TCV in spaces PV and LS rose but did not change significantly. In stage 3, TCV decreased significantly in spaces OS and PR (p<0.05) but did not change significantly in spaces PV and LS. In stage 4, TCV continued to decrease in space OS (p<0.05). This indicated that elderly adults' thermal discomfort was not improved after 15 min of recovery in space OS (Fig.5).



(a) (b)

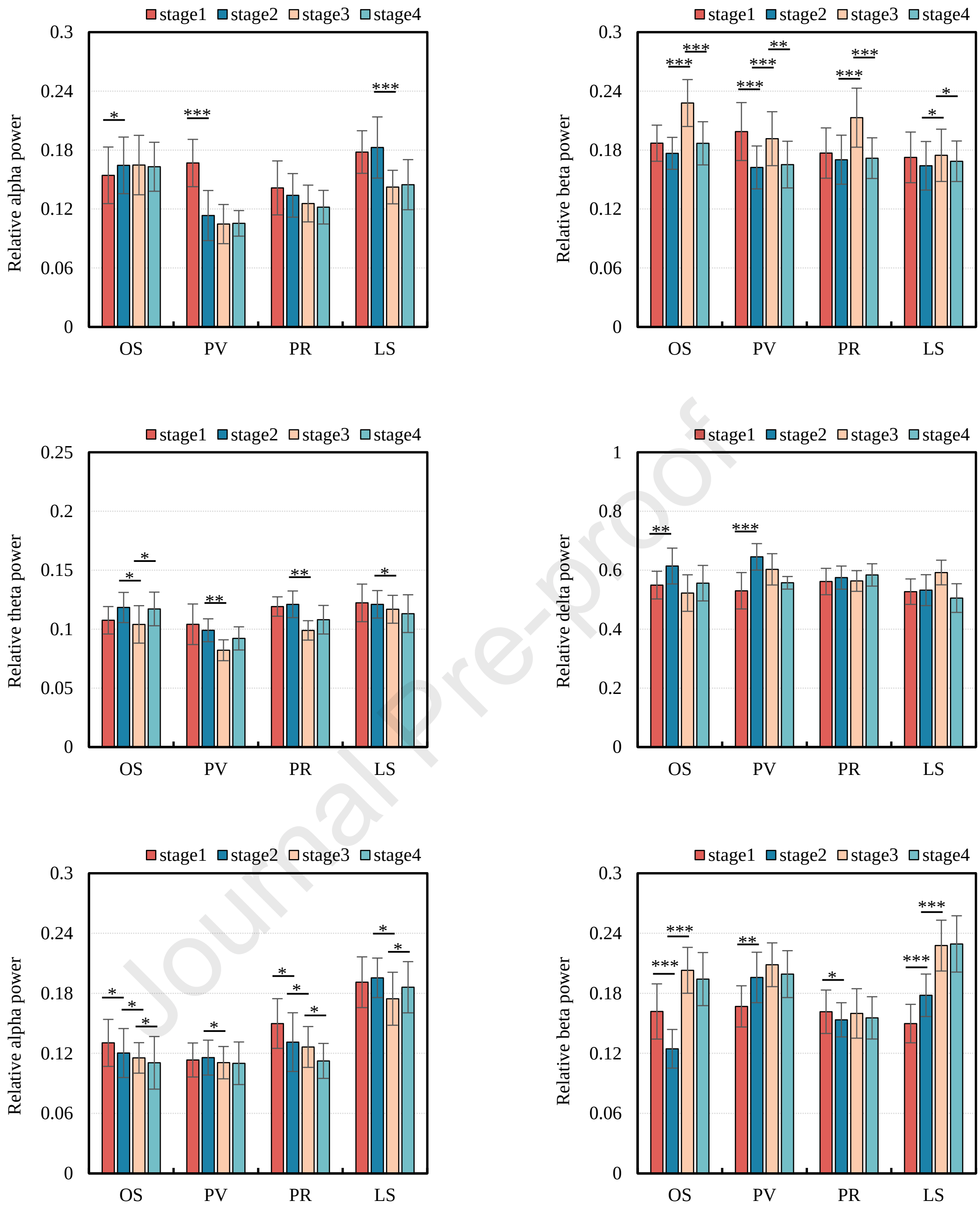
Fig.5. Thermal comfort vote in all four stages as defined in the text: spring (a) and summer (b) (* <0.05; ** <0.01).

3.3. EEG

In each season, nine volunteers participated in experiment in each space. EEG signal data were collected from 72 volunteers (spring: 36; summer: 36). To investigate the characteristics of EEG changes of elderly adults, a paired-sample t-test (sample size: 126) was performed on the relative powers of EEG signals in 14 channels of 9 old people at different experimental stages.

In spring, from stage 1 to 2, the α relative power increased in space OS (p<0.05), indicating that elderly adults felt relaxed here. The β relative power decreased in all experimental spaces, especially PV (p<0.001). The δ relative power increased in spaces OS (p<0.01) and PV (p<0.001). From stage 2 to 3, the α relative power in all spaces, except in OS, decreased. Of note, the α relative power decreased the most in space LS (p<0.001). The β relative power increased significantly in all spaces (p<0.05). The θ relative power decreased in all spaces (p<0.05), indicating a decline in respondent pleasure. From stage 3 to 4, the α relative power did not change while the β relative power decreased in all spaces (p<0.05). The θ relative power increased in space OS (p<0.05) indicating an increase in pleasure. Overall variation in the EEG readings suggests that the comfort of elderly adults was the highest in space OS at all stages, due because elderly adults accepted relatively high T_a and G in spring.

In summer, from stage 1 to 2, the α relative power decreased in spaces OS and PR (p<0.05) but did not change in spaces LS and PV. The β relative power increased significantly at PV and LS but declined in the other two spaces. This implied that elderly adults felt more alert in spaces PV (p<0.01) and LS (p<0.001). The θ relative power increased significantly in space LS (p<0.001), suggesting that elderly adults experienced greater pleasure here. The δ relative power increased in spaces OS (p<0.001) and PR (p<0.05), indicating that the relatively high T_a made elderly adults feel sleepier, or less alert, in these spaces in summer. From stage 2 to 3, the α relative power of elderly adults declined in all four spaces (p<0.05), whereas the β relative power increased, especially in spaces OS and LS (p<0.001). There was no significant difference in the θ relative power before and after the stress test. The δ relative power decreased in all spaces (p<0.05). From stage 3 to 4, the α relative power continued to decrease in spaces OS and PR (p<0.05), but increased significantly in space LS (p<0.05). In spaces OS, PV and PR, the β and θ relative powers decreased, while δ relative power increased. Overall EEG readings in the summer suggest that elderly adults felt the most uncomfortable in space OS, which we attribute to high T_a and direct solar radiation. They found the thermal environment more comfortable in spaces PV and LS, with the comfort level in space LS significantly higher than that in space PV. This we attribute to the abundant plants in space LS (Fig.6; *Appendix Table C*).


stage1 stage2 stage3 stage4
Relative alpha power
Relative beta power
Relative theta power
Relative delta power
OS
PV
PR
LS

(a)

(b)

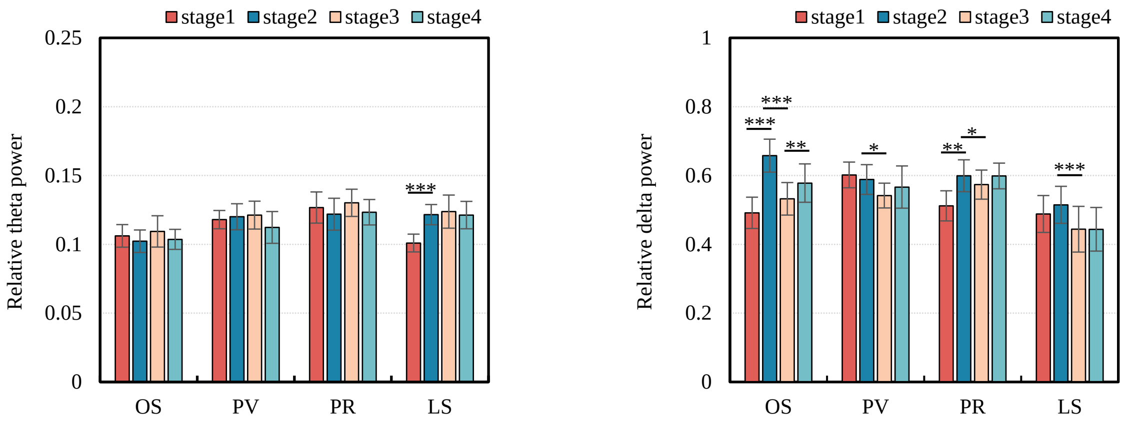


Fig.6. Relative power changes in the four stages as described in the text: spring (a) and summer (b) (* <0.05; ** <0.01; ***<0.001).

3.4. Factors influencing the EEG

3.4.1. Meteorological parameters

In spring, the α relative power in four cerebral cortex regions of elderly adults were significantly and negatively correlated with V_a (p<0.01), indicating that respondents felt relaxed and calm as V_a decreased. The δ relative power of the frontal lobe was significantly and positively correlated with V_a, but the θ relative power was negatively correlated with V_a (p<0.01). With an increase of V_a, respondents felt sleepier and less happy. The β relative power of frontal lobe had a significant and positive correlation with T_a and RH (p<0.05).

In summer, the α, δ and β relative powers at the parietal lobe were strongly correlated with outdoor meteorological parameters. The θ relative power was not correlated with outdoor meteorological parameters. The α relative power was negatively correlated with PET, T_g and T_a (p<0.05), and positively correlated with RH (p<0.05). The β relative power was negatively correlated with PET, T_g, T_a, and T_{mrt} (p<0.05), and positively correlated with RH (p<0.05). The δ relative power was positively correlated with PET, T_g, T_a, and T_{mrt} (p<0.05), and negatively correlated with RH (p<0.05). Generally, with an increase in T_a or decrease in RH, elderly adults generated more negative emotions such as sleepiness or nervousness, in summer. EEG signals in the occipital and temporal lobes were relatively weakly correlated with meteorological variables. Similar to the parietal lobe, the δ and β relative powers at the frontal lobe were strongly correlated with outdoor meteorological parameters (p<0.01). Additionally, the θ relative power at the frontal lobe was negatively correlated with PET, T_g, V_a, T_{mrt}, and G (p<0.05), and positively correlated with RH (p<0.05). The α relative power at frontal lobe was relatively weakly correlated with meteorological variables, opposite of the parietal lobe.

Correlations between meteorological variables and EEGs of elderly adults were relatively weak in spring. Correlations increased significantly in summer. In particular, the δ, θ, and β relative powers of the frontal lobe were strongly correlated with PET, T_g, V_a, T_{mrt}, and G. The α, δ and β, relative powers of the parietal lobe were significantly correlated with PET, T_g, T_a, and RH. The δ, θ, and β relative powers of the frontal lobe and the α, δ, and β relative powers of the parietal lobe can be used to evaluate effects of the measured outdoor meteorological parameters on the psychological states of elderly adults (Fig.7; *Appendix Table D*).

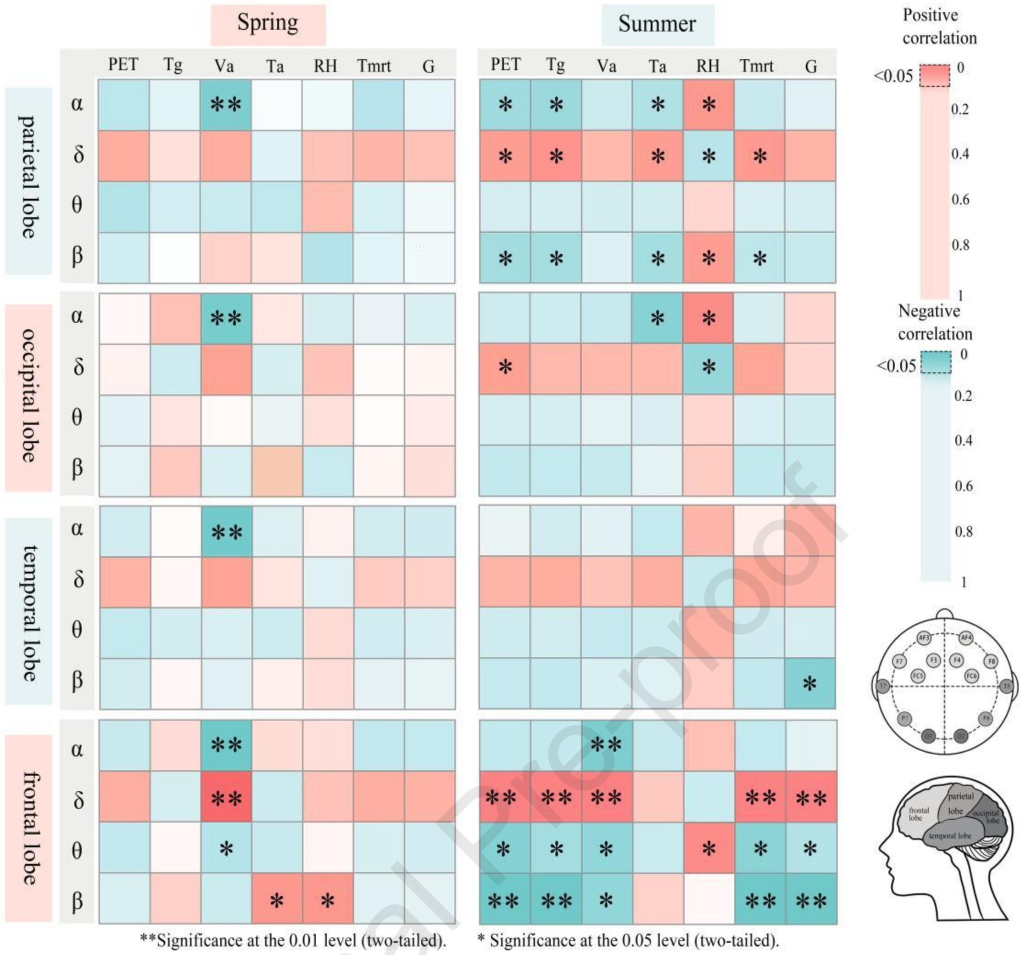


Fig.7. Correlation analysis of meteorological parameters and EEG.

3.4.2. TSV and TCV

The variation in α and β relative powers at the cerebral cortex of elderly adults differed significantly with variable thermal sensations. The α relative powers of F3, FC5, FC6, F4, F8, AF4, and F7 channels had an "inverted U" shape, varying with an increase in thermal sensation. When TSV changed from "neutral" to "slightly warm", the α relative power of these channels increased (p<0.05). When TSV changed from "slightly warm" to "hot", the α relative power of above channels decreased (p<0.05). The β relative power of T7 reached its highest when the elderly adults felt "slightly warm". Clearly, they felt most relaxed when they perceived the space to be "slightly warm". With a TSV increase, the α relative power of most channels in the frontal lobe increased and then decreased. Hence, the α wave of the frontal lobe can be used as an index to accurately reflect thermal sensation variation in elderly adults (Fig.8; *Appendix Table E*).

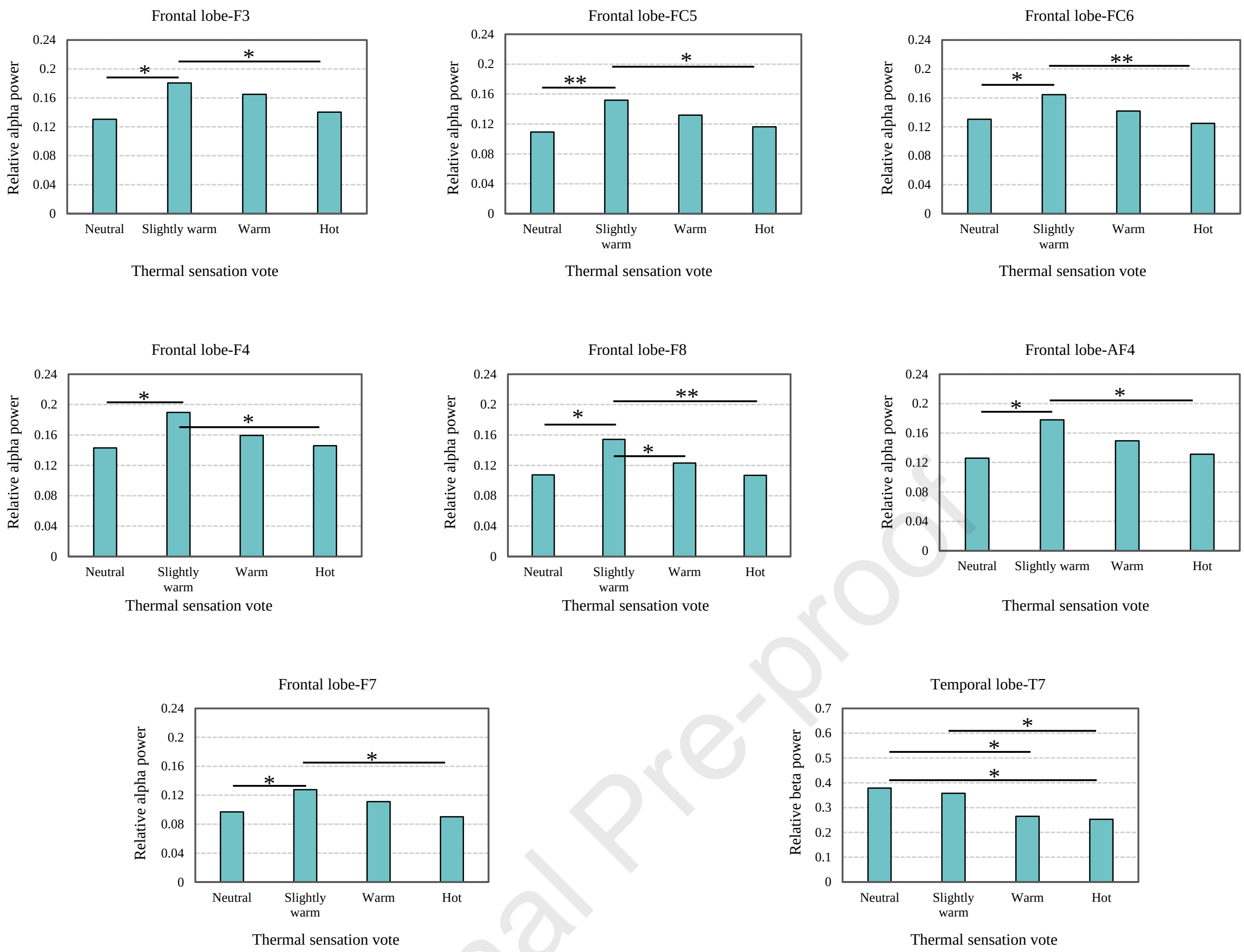


Fig.8. Relative power changes on thermal sensation vote at each measured point (*<0.05; **<0.01).

The variation in α, θ, and δ relative powers at the right cerebral cortex of elderly adults differed significantly with varied thermal comfort. With an increase in TCV, the α relative powers of AF4, F4, FC6 and F8 channels at the right frontal lobe (p<0.05), the O2 channel at the right occipital lobe (p<0.01), and P8 channel at the right parietal lobe increased (p<0.05). In addition, the θ relative power of F4 channel at the right frontal lobe increased gradually when TCV changed from “uncomfortable” to “comfortable”, while the δ relative power of O2 channel at the right occipital lobe decreased significantly (p<0.05). This suggests that with an increase in thermal sensation, elderly adults feel happier and less sleepy. It is evident that the right cerebral cortex of our respondents was more sensitive to variation in thermal comfort. Furthermore, with TCV changes, the α wave varies significantly in many channels at the right cerebral cortex compared to β, θ, and δ waves. Hence, the α wave at the right cerebral cortex, especially the O2 channel at the occipital lobe, can be used to predict elderly adults' thermal comfort (Fig.9; *Appendix Table F*).

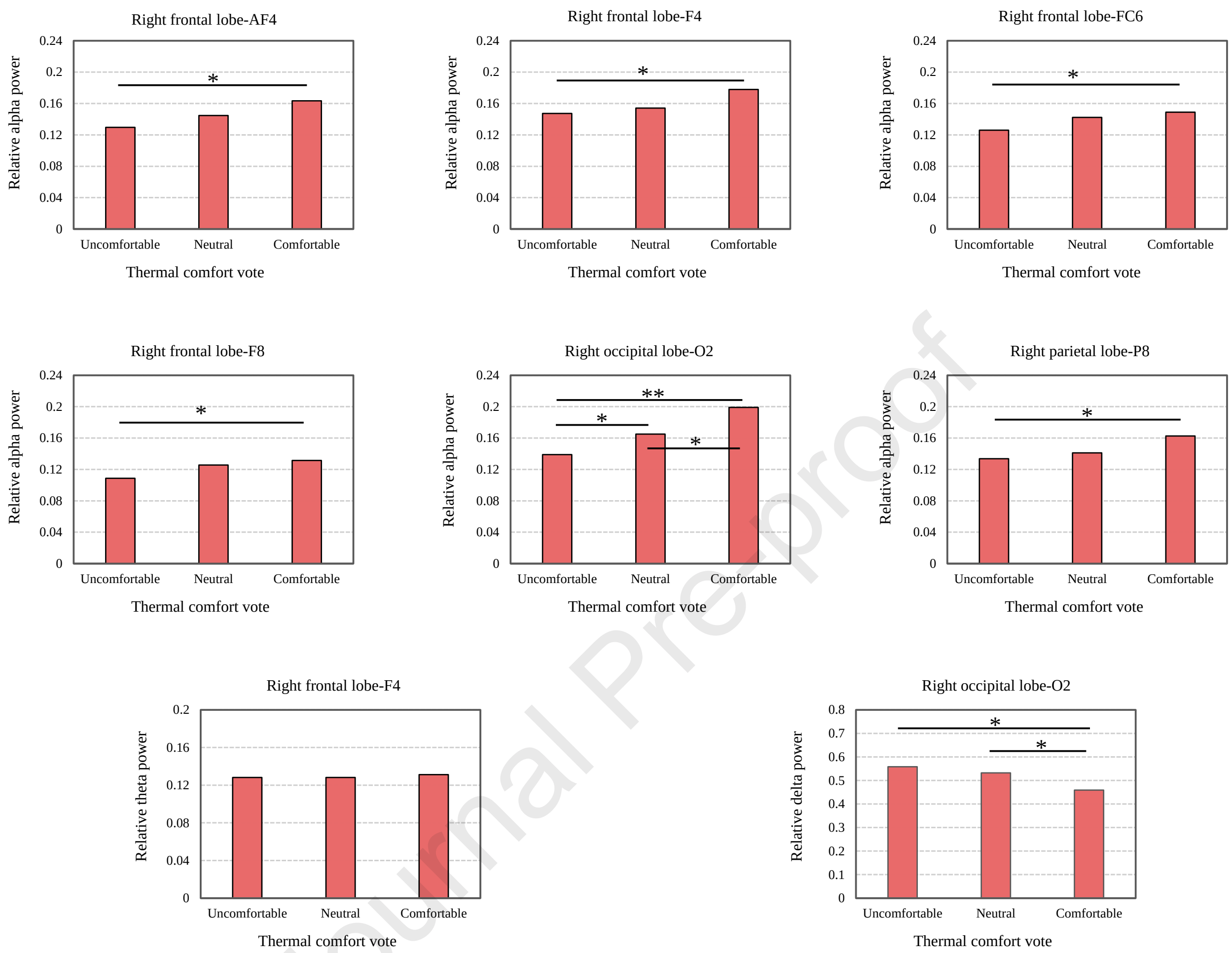


Fig.9. Relative power changes of thermal comfort vote at each measured point (*<0.05; **<0.01).

3.5. Relationships between thermal perceptions and EEG

Mean TSV at three stages (2, 3, and 4) corresponding to a 1°C PET bin interval was calculated and fitted to a linear model. PET during trials was divided into four intervals according to thermal sensation of elderly adults: 19.9–28.9°C (neutral), 28.9–38.0°C (slightly warm), 38.0–47.0°C (warm) and 47.0–51.5°C (hot). These intervals represented thermal stress temperature ranges for elderly adults in outdoor open spaces (Fig.10).

For each PET interval, correlations between the relative powers of the four EEG frequency bands among all respondents and corresponding meteorological variables were analyzed. A standardized coefficient was obtained by regression, controlling for the influence of dependent variables and independent variables units. The standardized coefficient divided by the sum of absolute values of all standardization coefficient provides a parameter weight that estimates the influence of meteorological variables on the four EEG frequency bands; higher weights indicate greater influence on EEG. A variance inflation factor (VIF) smaller than 10 indicates no multi-collinearity among parameters [41].

Within the PET range of 19.9–28.9°C (neutral), the α relative power was influenced by T_a, T_g and V_a. It was negatively related to T_a, T_g, and V_a. G had a significant effect on β relative power. The δ relative power was only influenced by V_a and the θ relative power was not affected by meteorological parameters within this range (Table 3).

In the PET range of 28.9–38.0°C (slightly warm), the effect of V_a on α relative power was strengthened, increasing from 19.37% to 72.18%. T_{mrt} began to influence the α relative power, but the effect was slight. In this interval, the β relative power was only sensitive to T_a, but the θ relative power began to be affected by T_g, T_{mrt}, T_a and RH. The effect of T_g on the θ relative power was the most significant, while influence of V_a on δ relative power decreased from 100% to 54.18%. Additionally, T_g began to influence the δ relative power (Table 4).

Within the PET range of 38.0–47.0°C (warm), V_a had no effect on α relative power and T_{mrt} became the primary influencing factor. The β relative power began to be influenced by RH, T_g and G and the effects of T_a and T_{mrt} on θ relative power began to increase. G and RH began to affect the δ relative power and the influence of T_g declined (Table 5).

Within the PET range of 47.0–51.5°C (hot), G was the dominant influencing factor of the α relative power, and the influence of T_g decreased significantly. The effect of T_a on β relative power continued to decrease, and V_a had a large impact on the β relative power. The θ relative power was primarily influenced by RH and T_a. The δ relative power was no longer influenced by T_g and RH, while the effect of V_a increased (Table 6).

Generally, T_a and V_a had the greatest effect on EEG readings among elderly adults. Under different thermal stresses, there were varying meteorological factors that influenced their EEGs. At "neutral" sensation trials, there were few meteorological variables that influenced EEG readings. This demonstrated that meteorological parameter changes had little influence on physiology and psychology of elderly adults within this PET interval. With an increase of PET, the number of meteorological factors that influenced the EEG of elderly adults increased gradually. This indicated that, under a higher thermal stress, the sensitivity of EEG to meteorological parameters increases.

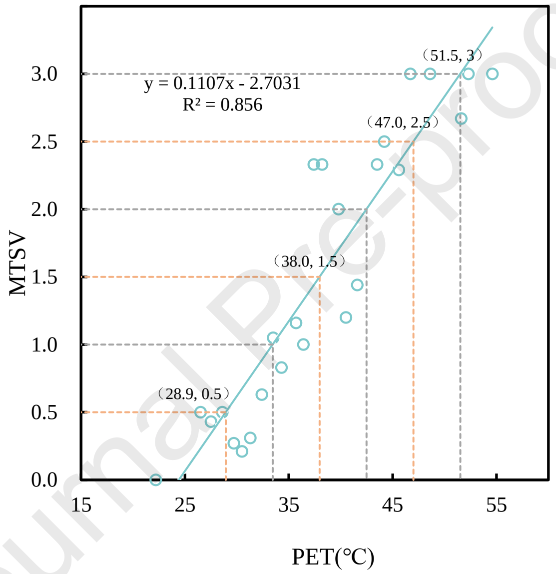


Fig.10. Correlation between PET and MTSV.

Table 3. Multiple linear regression analysis for the relative power of EEG bands at 19.9–28.9℃.

		Parameters	R^2	Standardized coefficients	Parameter weight	Sig.	Collinearity statistics (VIF)
TSV [-0.5, 0.5)	α	(Constant)	0.281				
		T_a		−1.033	44.26%	.000	7.497
		T_g		−0.849	36.37%	.000	7.385
		V_a		−0.452	19.37%	.000	1.074
	β	(Constant)	0.193				
		G		−0.316	100%	.000	1.000
	θ	—	—	—	—	—	—

	δ	(Constant)	0.246				
		V_a		0.230	100%	.006	1.000

Table 4. Multiple linear regression analysis for the relative power of EEG bands at 28.9–38.0℃.

		Parameters	R^2	Standardized coefficients	Parameter weight	Sig.	Collinearity statistics (VIF)
TSV [0.5, 1.5)	α	(Constant)	0.163				
		V_a		−0.288	72.18%	.000	1.267
		T_{mrt}		−0.111	27.82%	.016	1.267
	β	(Constant)	0.110				
		T_a		0.110	100%	.009	1.000
	θ	(Constant)	0.189				
		T_g		−0.727	44.22%	.000	7.660
		T_{mrt}		−0.481	29.26%	.000	5.470
		T_a		−0.330	20.07%	.000	4.345
		RH		0.106	6.45%	.016	1.165
	δ	(Constant)	0.153				
		V_a		0.175	54.18%	.000	1.006
		T_g		0.148	45.82%	.000	1.006

Table 5. Multiple linear regression analysis for the relative power of EEG bands at 38.0–47.0℃.

		Parameters	R^2	Standardized coefficients	Parameter weight	Sig.	Collinearity statistics (VIF)
TSV [1.5, 2.5)	α	(Constant)	0.460				
		T_{mrt}		−0.860	43.61%	.000	2.272
		RH		0.776	39.35%	.000	2.366
		T_g		−0.336	17.04%	.000	1.851
	β	(Constant)	0.472				
		T_a		−1.300	29.45%	.000	5.074
		T_g		−1.221	27.66%	.000	3.273
		RH		0.908	20.57%	.000	2.977
		G		−0.985	22.32%	.000	3.669
	θ	(Constant)	0.354				
		T_a		−1.062	40.11%	.000	4.984
		T_{mrt}		−1.100	41.54%	.000	7.850
		T_g		−0.486	18.35%	.001	5.267
	δ	(Constant)	0.387				

G	0.403	31.88%	.000	1.115
RH	−0.387	30.62%	.000	2.757
T_g	0.271	21.44%	.003	2.036
V_a	0.203	16.06%	.013	1.620

Table 6. Multiple linear regression analysis for the relative power of EEG bands at 47.0–51.5℃.

		Parameters	R2	Standardized coefficients	Parameter weight	Sig.	Collinearity statistics (VIF)
TSV [2.5, 3.0)	α	(Constant)	0.314				
		G		−1.140	51.24%	.000	4.753
		T_{mrt}		−0.871	39.14%	.000	3.683
		T_g		−0.214	9.62%	.031	1.540
	β	(Constant)	0.469				
		V_a		−0.803	47.91%	.000	1.560
		T_a		−0.449	26.79%	.000	1.427
		T_g		−0.424	25.30%	.000	1.470
	θ	(Constant)	0.387				
		RH		1.580	56.98%	.000	2.853
		T_a		−1.193	43.02%	.000	1.853
	δ	(Constant)	0.372				
		T_a		0.600	36.72%	.000	1.576
		V_a		0.553	33.84%	.000	1.358
		G		0.481	29.44%	.000	1.190

4. Discussion

4.1. Meteorological parameters and EEG

The β relative power in the frontal lobe of elderly adults is positively correlated with T_a and *RH* in spring. Increasing T_a and *RH* can make elderly adults more alert and improve positive emotions. Additionally, in four cerebral cortex regions among elderly adults, the α relative power is significantly and negatively correlated with V_a. This indicates that elderly adults become more anxious and nervous with an increase of V_a in spring. Okamoto et al. found that overall human comfort is higher in windless environments [42], consistent with our results. In spring, increasing V_a may accelerate air drying in the spaces we measured, resulting in naturally lower *RH* and intensifying discomfort for elderly adults that is manifest by sleepiness. In summer, the influence of V_a on EEG of elderly adults is weakened, while influence of T_a, T_g, RH, and T_{mrt} are strengthened. Ma et al. also reported that T_a, T_g, and RH are the primary influencing factors of thermal perception among elderly adults, while V_a shows the least influence [43].

EEG at both the frontal and parietal lobes can be used to measure the effects of meteorological variables on elderly adults' psychological states. The feeling of fatigue that accompanies thermal stress is related with frontal cortex activity [44]. With changes in T_{mrt}, the β wave at the frontal lobe also varies significantly [29]. With increasing T_a, the δ relative power at the frontal lobe increases significantly, but θ and β relative powers decrease significantly. Consistent with the results of our study, Zhu et al. also reported that RH changes induce changes of δ and θ relative powers in the frontal lobe [30]. The parietal lobe processes and receives sensory information, connecting all organs in the body [45]. Hence, meteorological variables may cause EEG changes at the parietal lobe once they act on human body. Comparing to five different radiation panel temperatures for 60 min, i.e., 100, 150, 200, 250, and 300 °C, at 0.8 m from the radiant panel, the α activity of parietal lobe has the smallest vibration amplitude at 250°C [29]. The θ relative power at the parietal lobe is not significantly correlated with meteorological parameters in summer. This is primarily because most θ waves distribute in the frontal lobe and central areas, while some appear at the parietal and temporal lobes [46]. The relative power of the EEG is more likely to change significantly at high T_a. The δ wave activity at 32°C is far higher than that at 25°C [47], which is similar to our results.

4.2. TSV and EEG

The α relative powers of most channels (F3, FC5, FC6, F4, F8, AF4 and F7) in the frontal lobe have different variation characteristics with thermal sensation changes. Hence, the α wave at the frontal lobe can be used as an index to accurately reflect thermal sensation changes among elderly adults. Asymmetric activities of EEGs in the frontal lobe are related to subjective responses [37]. The α wave is distributed extensively at the cerebral cortex and reflects its activities, especially when people are in relaxed, calm and stable states [30]. Yao et al. reported that ambient temperature affects the EEG power of different frequency bands, especially the α wave [23]. With an increase in thermal sensation, the α relative power decreases [48]. In our study, the α relative power peaks when elderly adults feel "slightly warm". Due to the decreased metabolic rate and thermoregulatory ability, elderly adults have significantly different thermal sensations from other age groups, preferring higher T_a [10, 49]. In addition, the β relative power of the T7 channel at the temporal lobe is significantly different under varied thermal sensation and reaches its maximum when elderly adults feel "slightly warm". The β wave is the usual waking rhythm of the brain associated with active thinking or active attention [37]. With an increase of thermal sensation, the β relative power decreases and elderly adults find it more difficult to think clearly. However, the temporal lobe is typically related to auditory stimuli, memory perception and recognition [30].

4.3. TCV and EEG

The right cerebral hemisphere of elderly adults is sensitive to thermal comfort changes. Han et al. found that compared with thermal displeasure, the cerebral cortex and frequency bands that can reflect thermal discomfort increase significantly, including specific frequency bands in the central, frontal and parietal lobes. In our study, thermal discomfort changes were based on gradual temperature variation, which was a type of low arousal stimulus. Under these conditions, EEG does not change in specific regions and frequency bands, but tends to change in overall energy [24]. Thermal comfort of elderly adults is based on gradual, rather than sudden, changes in outdoor thermal environments, related to low arousal stimulus. However, EEG changes concentrate at the right hemisphere, which differs from what Han et al. concluded [24]. In fact, the asymmetric activities of brain are related with emotional recognition. Activity in the left cerebral hemisphere is more correlated with positive/approach emotions, while the right cerebral hemisphere is more related to negative/withdrawal emotions [50–52]. Some studies have pointed out that asymmetric brain activity is related with thermal comfort. Shan et al. found that under thermally neutral conditions, EEG asymmetry at the frontal lobe is the highest [37]. We found that, compared with the β, θ, and δ waves, α wave changes significantly in many channels of the right hemisphere as thermal comfort varies. This is especially the case in the O2 channel of the occipital lobe, consistent with the findings of Emília et al. [53]. Lang et al. found that the α wave of the P7 channel is the most appropriate single channel to detect thermal comfort changes [48]. This is somewhat consistent with our results that we attribute to different experimental conditions between the two studies. The variation of human comfort in the Lang et al. study was stimulated by four temperatures levels. However, in our study, thermal comfort changes were created by the mixed effects of multiple outdoor environmental factors. EEG signal changes also vary among different environmental stimuli [24].

4.4. Implications for designs

We found that microclimate significantly affected EEG signals among elderly adults, relative to their thermal comfort. Our results contribute to the practical bioclimatic design of outdoor open spaces in an urban environment, potentially and the improvement of outdoor thermal comfort of the elderly. In spring, most elderly people feel "neutral" and "slightly warm" (19.9≤PET<38.0°C). V_a was the primary factor that affected the EEG signal; decreasing V_a helps the elderly feel more relaxed and happy, as well as alleviating sleepiness. Urban designers can create semi-open spaces with plants, using evergreen trees (*Platycladus orientalis* and *Magnolia grandiflora*) on the windward side. Evergreen shrubs (*Buxus megistophylla*, *Pittosporum tobira* and *Euonymus alatus*) could be planted appropriately in resting places to improve the aesthetic and decrease the V_a.

In summer, decreasing T_a and increasing *RH* are effective ways to alleviate thermal discomfort among elderly residents. Spraying facilities could be set around the rest spaces for the elderly, and environmental design could provide adequate shade. In addition, with the increase in *G*, the α relative power decreased significantly among our respondents within the PET range from 47.0 to 51.5°C. Therefore, urban designers could use deciduous trees (*Styphnolobium japonicum*, *Zelkova serrata* and *Aesculus chinensis*) and use shade facilities (pavilions, pergolas, sunshades) to create cool spaces, thus reducing the adverse effects of excessive solar radiation on the physiology and psychology of older urban residents.

4.5. Limitations

Our study has some limitations. First, we focused on the relationship between outdoor thermal comfort and EEG of elderly adults in spring and summer during which there is high attendance of elderly adults. However, there is a high incidence of cardiovascular and cerebrovascular diseases for the elderly in winter, linked to the thermal environment during the cold season. Thus, the relationship between outdoor thermal comfort and EEG of the elderly in the cold season should be further studied using the similar methodology. Second, elderly adults participate in a variety outdoor activity types that span a range of intensities. We only examined thermal perceptions as elderly adults sat statically. It may be necessary to include more activity types in future research. Third, future studies should combine more physiological indices, such as ST, ECG and HR to more accurately reflect elderly adults' thermal comfort.

5. Conclusions

In this study, the relationship between thermal comfort and EEG (α, β, θ and δ frequency bands) of elderly adults were studied in four common outdoor open spaces in Xi'an, China. We measured ambient metrological variables, subjective thermal comfort through a questionnaire survey and EEG signals of respondents. We concluded:

1) The δ, θ, and β relative powers of the frontal lobe were significantly correlated with PET, T_g, V_a, T_{mrt}, and G. The α, δ, and β relative powers of the parietal lobe were significantly correlated with PET, T_g, T_a, and RH. The δ, θ, and β relative powers of the frontal lobe and the α, δ, and β relative powers of the parietal lobe can be used to predict the effect of meteorological parameters on elderly adults' psychological state.

2) With an increase in TSV, the α relative powers of F3, FC5, FC6, F4, F8, AF4, and F7 at the frontal lobe formed an inverted U-shape curve. When elderly adults feel "slightly warm", the α

relative power peaked. The α wave at the frontal lobe can accurately reflect elderly adults' thermal sensation changes.

3) The right cerebral hemisphere was more sensitive to thermal comfort changes than the left. With an increase of TCV among elderly adults, the α relative powers of AF4, F8, FC6, F4 channels in the right frontal lobe, the O2 channel in the right occipital lobe and the P8 channel in the right parietal lobe increased significantly. The α wave in the right hemisphere, particularly the O2 channel in the occipital lobe, can be used to reflect elderly adults' thermal comfort.

4) T_a and V_a had the most influence on EEG among elderly adults. Meteorological factors that affected EEG varied under different thermal stresses, and these factors were positively related to thermal stresses.

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Highlight

1. We investigated relationships between OTC and EEG among Xi'an elderly residents.
2. The α index of frontal lobe can be used to evaluate thermal sensation of the elderly.
3. The α wave of right cerebrum, particularly the O2 channel, reflected thermal comfort.
4. T_a and V_a had the greatest effects on EEG among elderly residents.

Declaration of 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.