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Investigating the relation between electroencephalogram, thermal comfort, and cognitive performance in neutral to hot indoor environment

Xiaoyue Lang[1] | Pawel Wargocki[2] | Weiwei Liu[1]

[1]Central South University, Changsha, China

[2]Technical University of Denmark, Kongens Lyngby, Denmark

Correspondence
Weiwei Liu, Central South University, Changsha, China.
Email: wliu@csu.edu.cn

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Abstract

The relation between electroencephalogram signals, thermal comfort, and cognitive performance in neutral to hot indoor environment was investigated. The experiments were carried out at four temperatures: 26°C, 30°C, 33°C, and 37°C, and two relative humidity levels: 50% and 70%. Thirty-two subjects were exposed for 175 min. The electroencephalogram signals were measured for 30 min 25 min after the onset of exposure while the recruited subjects performed neurobehavioral tests and rated their thermal comfort. The relative power of electroencephalogram signals has a significant correlation with thermal comfort and performance of neurobehavioral tests. The ratings of acceptability of thermal environment and thermal comfort, the speed, accuracy, and PI of completing the tests are negatively correlated with the relative power of δ-band, but positively correlated with θ-band, α-band, and β-band. The ratings of thermal sensation have a better correlation with the above four bands, but the correlation trend is opposite. A linear relation was found between electroencephalogram signals and the speed. The results showed that the relative power of P7 channel located in the occipital lobe is the most suitable as a single electroencephalogram channel to reflect joint thermal comfort and cognitive performance at high temperatures, especially its α-band.

KEYWORDS
acceptability of thermal environment, cognitive performance, electroencephalogram, occipital lobe, thermal comfort, thermal sensation

1 | INTRODUCTION

With the frequent occurrence of high-temperature weather, the indoor temperature also rises. Field studies showed that the indoor temperature in some areas even exceeds 37°C.[1,2] The increased indoor temperature not only changes the thermal comfort of occupants,[3] but also affects their cognitive performance,[4,5] causing safety risks. People work and live indoors for a long time, so it is necessary to continuously evaluate the impact of rising indoor temperature on thermal comfort and cognitive performance.

In recent years, some physiological parameters have been used as objective indicators to continuously reflect thermal comfort. Most studies use parameters related to body temperature regulation, such as skin temperature, heart rate variability (HRV), electromyogram, sweat rate, and metabolic rate.[6–10] A few studies also have found that electroencephalogram (EEG) is related to thermal comfort. EEG, as a physiological parameter that has been continuously developed in the field of indoor environment, has attracted more attention from researchers. EEG is an electrophysiological monitoring method that records the electrical activity of the brain.[11] When people's perception of thermal comfort changes, the brain is activated.[12] Yao et al[13] measured the global relative EEG power of different bands at four temperatures and found that as the degree of thermal discomfort increased, the global relative EEG power of β-band increased as well. In another study, Lv et al[14] found that δ-band was significantly more active at 32°C than at 25°C. A recent study by Zhu et al[15] showed that increased relative humidity and increased temperature at high relative humidity caused measurable changes in EEG signals. The rapid changes of EEG signal provide convenience for measuring occupant's immediate response changes continuously.[16] Wu et al used an eight-channel wireless EEG recorder to record EEG signals and tried to continuously discriminate feelings of personal thermal comfort between uncomfortably hot and comfortable environments. When the temperature of the two rooms was 35°C and 26°C, and the relative humidity is 30%–60%, the accuracy of discrimination between thermal discomfort and thermal comfort can reach almost 90%.[17] All the above studies have shown that using EEG to quantify the thermal comfort of the occupants is a promising method.[18,19]

Unlike thermal comfort, there are few physiological parameters that can be used to reflect cognitive performance, and EEG is the more used one.[20] It records four frequency bands in Hz: delta (δ), theta (θ), alpha (α), and beta (β). δ-band (1 to 4 Hz) is related to sleep, θ-band (4 to 8 Hz) is related to drowsiness, α-band (8 to 14 Hz) is related to relaxed awareness without attention, and β-band (14 to 30 Hz) is related to active thinking.[21] Some preliminary psychological research base on EEG has been carried out. D'Rozario explored the relationship between neurobehavioral performance, alertness, and EEG and found that EEG can be used as a new alternative biomarker of neurobehavioural impairment and sleepiness in obstructive sleep apnea (OSA).[22] Gwak measured that the arousal level can be evaluated quantitatively by using EEG.[23] Dai et al[24] used EEG to classify the degree of difficulty of mental workload, and the four classification methods used can all have a classification accuracy of more than 75%. In Duraisingam's research, the results indicated that the EEG signals could reflect task difficulty level for program comprehension tasks for predicting easy and difficult tasks, and the overall correctly classified accuracy of 76.55% with a precision of 80.03%.[25] A recent study found that its proposed model based on EEG can yield recognition performance for learning tasks, with an accuracy of 92.9% in the subject-dependent approach and 77.2% in the subject-independent approach of learning tasks.[26] From the perspective of psychology, these studies fully illustrate the potential of EEG to establish a relation with cognitive performance.

However, the above-mentioned existing studies still have some limitations. (1) Almost all work is carried out within the range of ordinary temperature, and no high temperature is involved. Especially the psychological research on the relation between EEG and cognitive performance does not consider the influence of environmental temperature changes at all. Whether these results can be used in high-temperature environments remain to be further explored. (2)

Practical implications

1. The relative power of EEG signals is a potential physiological parameter for evaluating thermal comfort and cognitive performance in high-temperature environments.
2. Compared with other lobes of the brain, the EEG signals in the occipital lobe have a better relation with thermal comfort and cognitive performance.
3. The relative power of α-band of P7 channel located in the occipital lobe is most suitable for evaluating the joint effects of high temperature on thermal comfort and cognitive performance.

The existing studies do not pay attention to the relation between EEG, thermal comfort, and cognitive performance at the same time. Whether there are EEG signals that can simultaneously reflect thermal comfort and cognitive performance remains to be studied. (3) In the existing literature, more channels are used for EEG measurement, such as 64 channels. Obviously, the complicated measurement and data processing problems caused by more channels in EEG measurement will bring inconvenience to the practical application of EEG in the future. Considering this limitation, an interesting question worth exploring is whether a small number of channels of EEG can be used to reflect thermal comfort and cognitive performance?

Based on the climate-controlled experiment, this study explored the relation between EEG, thermal comfort, and cognitive performance in neutral to hot indoor environment. The main innovative contents are as follows: (1) The feasibility of using the relative power of EEG signals to reflect thermal comfort and cognitive performance under high indoor temperature is analyzed; (2) The most suitable EEG channel and its corresponding band that have the potential to reflect the thermal comfort and cognitive performance at the same time are determined. The results of this study provide a prospective theoretical basis for evaluating human thermal comfort and cognitive performance in high-temperature environments based on effective EEG channels in the future.

2 | METHODS

2.1 | Measuring protocol

The experiments were carried out in a climate chamber (W × L × H = 3.3 m×4 m × 2.8 m) at the Central South University in Changsha, China. Sixteen male and sixteen female healthy college students were recruited to participate in the experiments (Appendix S1). All subjects were non-smokers, and none had a history of cardiovascular diseases or hypertension; they were fluent in English. All subjects lived in Changsha, China, for at least one year before the commencement of experiments. Subjects were told not to sleep late, drink alcohol, or caffeine for at least 24 h before each experiment session. The subjects used their own clothing, which consisted of a short-sleeved T-shirt, thin trousers, sports shoes, socks, and underwear yielding the clothing insulation was about 0.39 clo.

The subjects were exposed to eight combinations of temperature and relative humidity. Four levels of temperature studied were as follows: 26°C, 30°C, 33°C, and 37°C, while two levels of relative humidity were 50% and 70%. The ventilation system supplied outdoor air into the chamber and maintained the ventilation rate at 1000 m^3/h. The ventilation rate was kept high to ensure that the air quality in the chamber did not affect the responses of the subjects. The average air velocity around subjects was kept below 0.1 m/s. The level of illumination was kept constant at 147 ± 24 lux.

The temperature of 26°C was designed as a neutral condition. According to the Chinese standard, it is also the lower limit set-point for air conditioning in public buildings in the summer.[27] The temperature of 30°C was selected as it is considered the temperature at which the hypothalamus begins to regulate the body temperature[28]; it is also likely to cause heat stress. The temperature of 33°C represents the average skin temperature of people who rest in a comfortable thermal environment[29,30]; it is also the temperature at which employees must be paid the so-called high-temperature weather subsidy according to the Chinese law.[31] The temperature of 37°C is close to the core temperature for a human; it is also recommended in China that outdoor activities should be avoided at this temperature to prevent heatstroke.[32]

The relative humidity of 50% was chosen because it was suggested as a lower limit of thermal comfort in some tropical countries.[33] The relative humidity of 70% is a common level indoors in tropical and subtropical climates[34,35]; it is also considered to be the upper limit for achieving thermal comfort in hot and humid environments.[36,37]

Thirty-two subjects were randomly divided into eight groups of four subjects. Each group contained two females and two males; they were exposed in the chamber in pairs of the same gender. Each pair experienced eight different conditions in the design balanced for order of exposure using Latin Square. There is only one condition during each exposure, that is, the temperature and relative humidity of the chamber remain unchanged. The total exposure time was 175 min in each condition. One pair participated each day in the experiments from 13:00 to 15:55 and another from 16:30 to 19:25.

The experimental procedure is described in Figure 1a. EEG was measured 25 min after the onset of exposures. The measurement took 30 min. At the same time, the subjects performed the neurobehavioral tests. The EEG measurements commenced only once because subjects reported feeling somewhat uncomfortable when wearing EEG acquisition equipment for a too long time in the practice experiments. Immediately before and after EEG measurements, thermal responses were collected. The complete experimental procedure figure can be found in Reference 15.

EEG was measured by the EPOC + headset (EMOTIV Inc.) at a sampling frequency of 128 Hz; the Emotiv PRO software recorded the signals. The EEG data could be viewed in real-time. It was further processed in Matlab. Fourteen EEG channels and two reference channels (CMS and DRL) of the EMOTIV EPOC + offer optimal positioning for accurate spatial resolution. According to the internationally recognized 10–20 system, the position of the scalp electrodes was described and applied.[38] This system is based on the relationship between the location of an electrode and the underlying area of the cerebral cortex. The "10" and "20" refer to the fact that the actual distances between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. The common mode sense (CMS) is on the left side of the brain, and the driven right leg (DRL) is on the right side. These two electrodes form a feedback loop, which drives the average potential of the subject (the Common Mode voltage) as close as possible to the ADC reference voltage in the AD-box (the ADC reference can be considered as the amplifier "zero"). The letters F, T, P, and O stand for frontal, temporal, parietal, and occipital lobes. The Fp stands for pre-frontal; AF is between Fp and F. The 14 EEG channels are located at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. They are located in the three main areas of the brain, the frontal lobe (AF3, F7, F3, FC5, FC6, F4, F8, and AF4), temporal lobe (T8, P8), and occipital lobe (P7, O1, P8, and O2). Figure 1b and c describe the EEG measurement.

Subjective responses were obtained using paper-based questionnaires in English (Figure 1d–f, these three votes constitute the thermal comfort questionnaire). The thermal sensation was evaluated on a nine-point extended continuous scale because the temperature and the relative humidity exceeded the range typically recommended for indoor environments. Thermal comfort and acceptability of thermal environment were evaluated on the scales with breakpoints in the middle separating either comfort/discomfort or acceptable/unacceptable thermal response. Subjective responses were collected just before and just after EEG measurements, and only these responses were used in the analyses. The responses on the continuous scales were rounded up or down to the nearest scale descriptor, so the scales were treated as discrete.

A neurobehavioral battery with cognitive tests was presented on a computer once the EEG was measured (Appendix S2). It was used to measure the effects on cognitive performance. It contained six computerized tests: Stroop, re-direction, overlapping, addition, multiplication, and visual learning; the detailed description of these tests can be found in Lan and Lian[39,40] and Liu et al.[41] The speed and accuracy were used as measures of performance. Speed is the number of questions completed per minute. Accuracy is the ratio of the number of questions answered correctly to the number of questions answered. Speed and accuracy were used to calculate the performance index (PI), which describes the number of correct questions completed per minute. The performance of different tests was normalized and integrated (averaged) to estimate the performance once the EEG was measured; we could not differentiate EEG signals for different performance tests. Speed, accuracy, and PI were integrated separately.

Figure 1a shows that during experiments, other measurements were also performed. They are described in detail by Zhu et al[15] and Fan et al.[42] In addition to EEG and cognitive performance, the

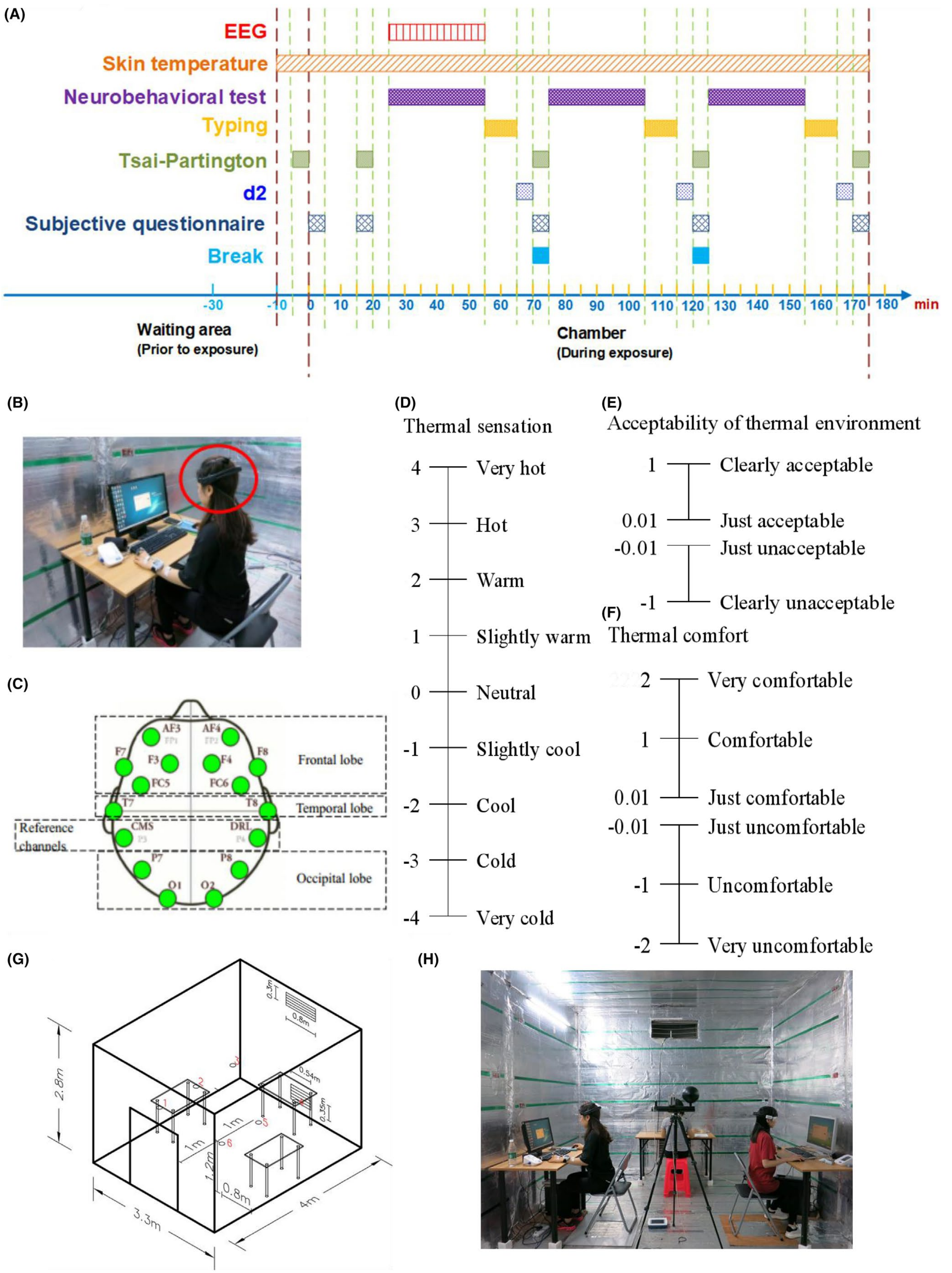
(A)
EEG
Skin temperature
Neurobehavioral test
Typing
Tsai-Partington
d2
Subjective questionnaire
Break
-30
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
min
Waiting area
(Prior to exposure)
Chamber
(During exposure)
(B)
(C)
AF3
AF4
F7
F3
F4
F8
FC5
FC6
Frontal lobe
T7
T8
Temporal lobe
Reference channels
CMS
DRL
P7
P8
O1
O2
Occipital lobe
(D)
Thermal sensation
4 Very hot
3 Hot
2 Warm
1 Slightly warm
0 Neutral
-1 Slightly cool
-2 Cool
-3 Cold
-4 Very cold
(E)
Acceptability of thermal environment
1 Clearly acceptable
0.01 Just acceptable
-0.01 Just unacceptable
-1 Clearly unacceptable
(F)
Thermal comfort
2 Very comfortable
1 Comfortable
0.01 Just comfortable
-0.01 Just uncomfortable
-1 Uncomfortable
-2 Very uncomfortable
(G)
2.8m
3.3m
4m
0.3m
0.8m
0.54m
0.35m
1m
1m
1.2m
0.8m
(H)

FIGURE 1 Overview of experiment. (a) Experimental procedure. (b) Measurements of EEG signals, EEG acquisition with EPOC + headset. (c) Locations of electrodes on the scalp. (d) The scale used to collect subjective responses describing thermal sensation. (e) The scale used to collect subjective responses describing acceptability of thermal environment. (f) The scale used to collect subjective responses describing thermal comfort. (g) The model of climate chamber, showing where the air velocity was measured at the height of 1.2 m. (h) The snapshot of the chamber during experiments

Tsai-Partington test results and the reported acute health symptoms (AHS) made immediately before and after the EEG measurement was also presented. The results of the Tsai-Partington test are often used as a proxy of arousal and cognitive performance.[43] Acute health symptoms provide information on whether there were any effects on aspects related to cognitive performance such as thinking difficulty, concentration, and fatigue.

All protocols were approved by the Ethics Review Board of The First Hospital of Hunan University of Chinese Medicine (AF/SC-07/02.0) and conformed to the guidelines contained within the Declaration of Helsinki. Oral and written informed consent to participate in the experiments were obtained from each subject.

2.2 | Data analyses

A detailed description of pre-processing can be found in Zhu et al.[15] EEGLAB toolbox (version14.0.0) running under the Matlab environment was used to pre-process EEG data; it includes removing artifacts and filtering frequencies. The artifacts such as eye blinks and muscle activities were removed by running the independent component analysis (ICA) algorithm in EEGLAB. The EEG contaminated with artifacts was input to ICA, then ICA separated the EEG and artifacts; finally, artifacts were rejected by the EEGLAB automatic EEG artifacts detector, and EEG was reserved for the next step of processing. A wave filter filtered out the waves below 1 Hz and above 30 Hz.

Brain activity was quantified by the relative power of four frequency EEG bands. The relative power is the ratio of the power of each band to the total power of the four bands. The artifact-free EEG data were processed with Matlab band power function to obtain the relative power of four frequency bands: δ, θ, α, and β. The process was conducted on 14 EEG channels, respectively, that is, the relative power of the four bands on each channel was calculated. The obtained relative EEG power of four bands at different exposure conditions was used in the statistical analyses.

Pearson correlation coefficient was used to analyze the correlation between EEG relative power of four frequency bands at all 14 channels, the thermal responses of subjects, and the performance of neurobehavioral tests under all experimental conditions. Correlation analysis was used to identify potential channels and bands of EEG that could be used to find the relation between EEG, thermal responses, and cognitive performance.

One-way ANOVA was used to evaluate the relation between subjective responses, neurobehavioral tests, and the relative EEG power. Subjective responses and the performance of neurobehavioral tests were used as the independent variables, while the relative EEG power was the dependent variable. The differences between the relative EEG power corresponding to different subjective responses or neurobehavioral test results were tested by post hoc analysis using the Bonferroni test.

The paired-samples *t* test was used to detect the differences between the relative EEG power for two subjective responses.

The test for linear trend was used to detect changes of acute health symptoms and performance the Tsai-Partington test along with the changes in thermal responses.

The SPSS (IBM SPSS Statistics) program was used. The level of significance was set at $p < 0.05$.

3 | RESULTS

3.1 | Physical parameters

Appendix S3 shows the intended and measured temperature and relative humidity: Temperature deviated by no more than 0.3°C and relative humidity deviation by no more than 2%. The conditions were considered as close to the intended level.

3.2 | Thermal comfort of subjects and neurobehavioral test results

Figure 2a–c show thermal comfort. As the temperature and RH increased, the responses gradually changed from acceptable to unacceptable and from comfortable to uncomfortable, while thermal sensation gradually changed from neutral to hot.

Figure 2d–f show the dimensionless results of neurobehavioral tests. They show that RH had a stronger effect than temperature, as shown in the previous study by Zhu et al.[15]

3.3 | Correlation analysis

The correlation analyses between EEG and thermal responses and cognitive performance are shown in Figure 3. The results show that the δ-band has the opposite trend to the other three EEG bands.

Figure 3a shows the correlation between the EEG relative power and the ratings of acceptability of thermal environment—9 of 14 EEG channels in the δ-band show the correlation, and 10 out of 14 EEG channels in the β-band show the correlation. For θ-band and α-band, only 4 and 3 EEG channels, respectively, show the correlation. This result suggests that δ-band and β-band can better represent the changes in acceptability of the thermal environment.

Figure 3b shows the correlation between EEG relative power and the ratings of thermal comfort. In this case, 13 of 14 EEG channels

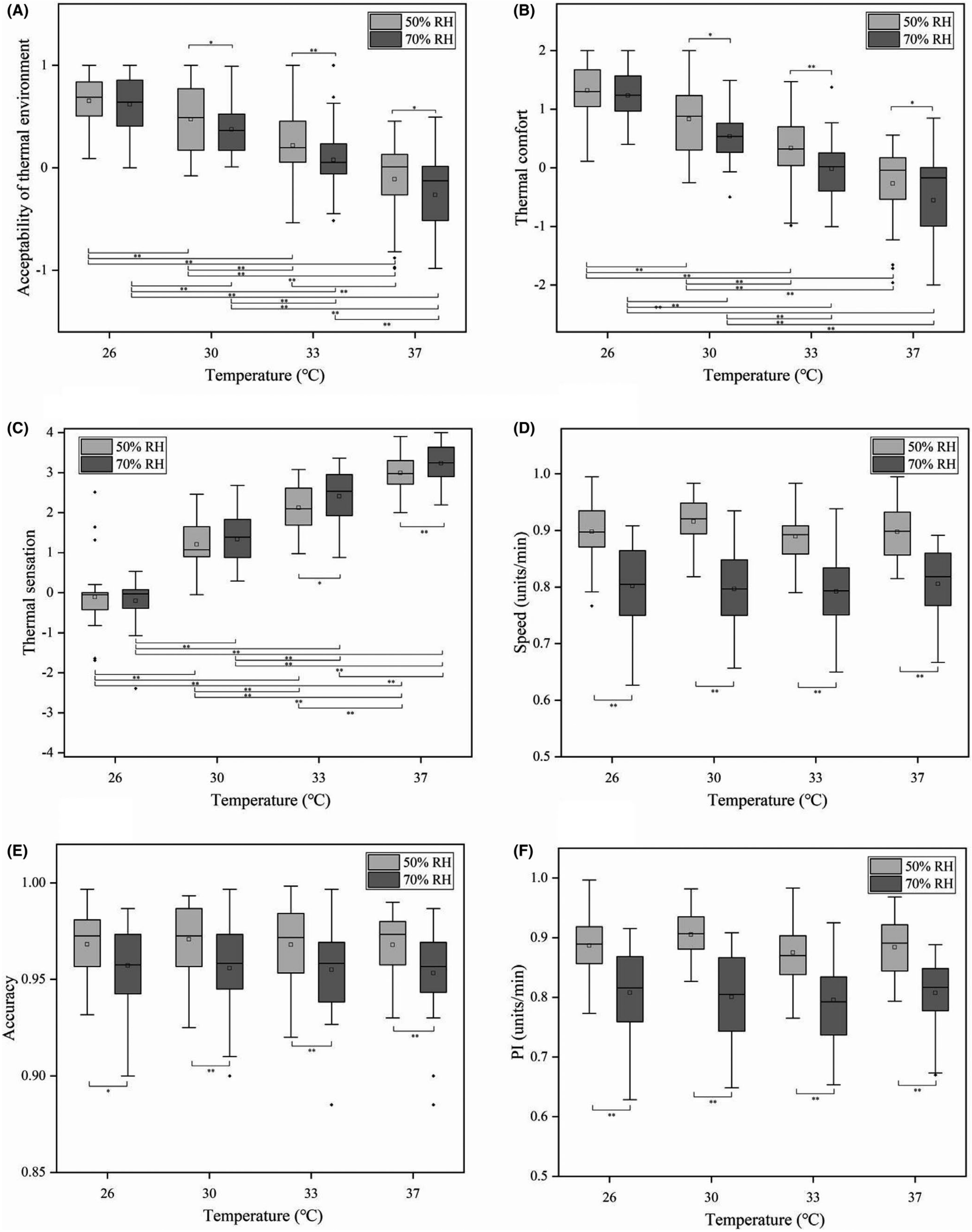

FIGURE 2 Thermal responses of subjects and neurobehavioral test results (normalized data). (a) Acceptability of thermal environment at different experimental conditions. (b) Thermal comfort at different experimental conditions. (c) Thermal sensation at different experimental conditions. (d) Average speed at which neurobehavioral tests were performed. (e) Average accuracy at which neurobehavioral tests were performed. (f) Average performance index (PI) at which neurobehavioral tests were performed

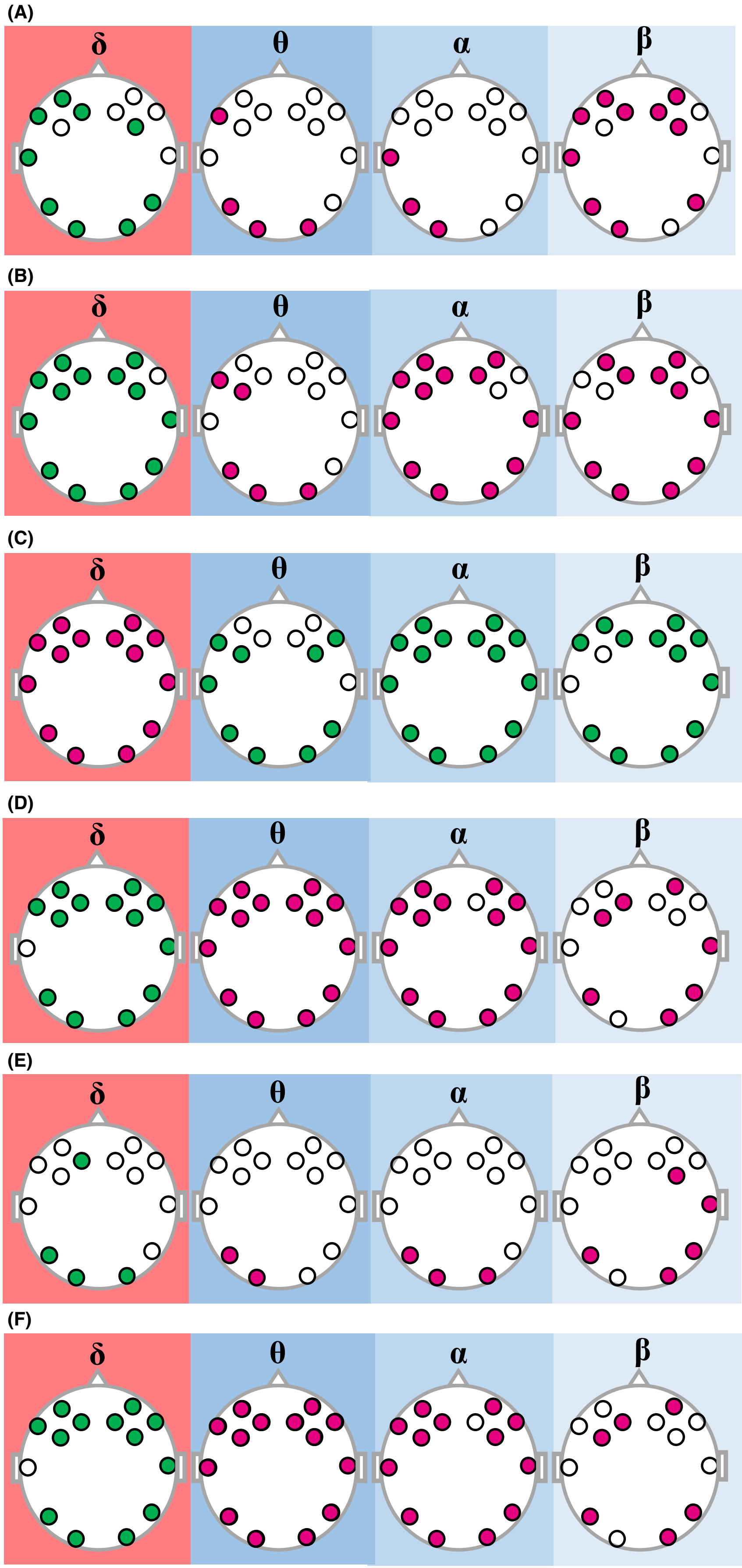

FIGURE 3 Correlation between EEG and thermal responses and cognitive performance, the colors represent a statistically significant correlation, green negative and red positive. (a) Correlation between the EEG relative power and ratings of acceptability of thermal environment. (b) Correlation between the EEG and the ratings of thermal comfort. (c) Correlation between the EEG relative power and ratings of thermal sensation. (d) Correlation between the EEG relative power and the speed at which neurobehavioral tests were performed. (e) Correlation between the EEG relative power and accuracy at which neurobehavioral tests were performed. (f) Correlation between the EEG relative power and PI

show the correlation for δ-band, while for α-band and β-band, 12 and 11 EEG channels, respectively, show the correlation. For θ-band, only 5 EEG channels show the correlation.

Figure 3c shows the correlation between EEG relative power and the ratings of thermal sensation. For δ-band and α-band, all 14 EEG channels show correlation. For β-band, 12 EEG channels show the correlation. For θ-band, 9 EEG channels show the correlation, which is more than half of the channels. Figure 3c suggests that EEG response is closely related to thermal sensation votes.

Figure 3d–f show a correlation between EEG relative power and the performance of neurobehavioral tests. Figure 3d shows that all 14 EEG channels in θ-band show the correlation for speed. For δ-band and α-band, 13 EEG channels show the correlation. For β-band, only 7 EEG channels show the correlation. Figure 3f shows the similar results for PI. Figure 3e shows that for accuracy, only a few EEG bands showed correlation. For δ-band, θ-band, α-band, and β-band, 4, 2, 3, and 5 EEG channels show the correlation, respectively.

3.4 | The relation between EEG and ratings of acceptability of thermal environment

Analyses were first performed on votes binned as follows: [−1, −0.5], (−0.5, −0.01], [0.01, 0.5), and [0.5, 1], but no significant relationships were found (Appendix S4). Acceptability ratings were then reclassified into two bins: unacceptable [−1, −0.01] and acceptable [0.01,1], and analyses were repeated. Table 1 summarizes the results for which the *t* test showed significant differences in relative power. P7 channel had three bands where significant differences were detected, and for all of the four bands of the O1 channel, significant differences were seen. In other words, these two channels were the ones that can be considered to be the best to detect changes in the ratings of acceptability of the thermal environment.

3.5 | The relation between EEG and the ratings of thermal comfort

Analyses were first performed on votes binned as follows: [−2, −1.5], (−1.5, −0.5], (−0.5, −0.01], [0.01, 0.5), [0.5, 1.5), [0.5, 1.5), and [1.5, 2] but no significant relationships were found (Appendix S5). The thermal comfort rating was reclassified into two bins: uncomfortable [−1, −0.01] and comfortable [0.01, 1]. The data were re-analyzed using a t test, and the detailed results are shown in Table 1. For 11 channels, significant differences were seen for the relative power of EEG corresponding to different ratings. The change from uncomfortable to comfortable ratings of the thermal environment increased the relative power of θ-band, α-band, and β-band significantly, and decreased the δ-band significantly. A similar change was seen in the case of assessments of acceptability of thermal environment. Significant differences between the two ratings have been detected in all O1 channel and O2 channel frequency bands. For the T8 channel, P7 channel, and P8 channel, each of them had three bands where significant differences were detected. The remaining six channels had only one or two bands where significant differences were detected. It is worth noting that the O1 channel, O2 channel, P7 channel, and P8 channel belong to the occipital lobe.

3.6 | The relation between EEG and the ratings of thermal sensation

Analyses were first performed on votes binned as follows: [−4, −3.5], (−3.5, −2.5], (−2.5, −1.5], (−1.5, −0.5], (−0.5, −0.5), [0.5, 1.5), [1.5, 2.5), [2.5, 3.5), and [3.5, 4]. The statistically significant results are shown in Appendix S6. From these figures, the results showed that 75% (24/32) of channels in the frontal lobe detected significant differences between different ratings, 75% (6/8) in the temporal lobe, and 93.8% (15/16) in the occipital lobe. This shows that the occipital lobe is probably more sensitive to heat. Although 93.8% of the EEG channels in the occipital lobe detected significant differences, none of them could detect significant differences between every two ratings. This means that we could not find one EEG channel that would predict the change in each rating. Consequently, two different classification methods A and B were proposed.

In another classification, method B, similar ratings were merged. Consequently, Slightly Warm and Warm were merged into one rating, Hot and Very Hot, into one rating, leaving out the Natural rating. Again the scale was reclassified from five points to three points. The results of the analyses are shown in Appendix S7. It shows the statistically significant differences for the δ-band of the P7 channel, like Table 1. The EEG bands with significant differences accounted for 53.1% (17/32) in the frontal lobe, 62.5% (5/8) in the temporal lobe, and 81.3% in the occipital lobe (13/16).

3.7 | The relation between EEG and the cognitive performance

Equidistance was used to bin speed and PI scores as follows: 0.75 – [0, 0.775), 0.85 – [0.775, 0.875), and 0.95 – [0.875, 100]; accuracy was binned as follows: 0.93 – [0, 0.945), 0.96 – [0.945, 0.975) and 0.99 – [0.975, 1]. The detailed results of the analysis are shown in Appendix S8. Figure 4 shows the channels where the highest number of significant differences was detected.

Figure 4a–c shows that all four bands of the P7 channel could distinguish differences in cognitive performance. Figure 4d–e show that all four bands of the O2 channel could distinguish differences in speed and PI, while Figure 4f shows the two bands that could distinguish the differences in accuracy.

4 | DISCUSSION

The present results suggest a relation between EEG, thermal comfort, and cognitive performance. Thermal sensation has been

TABLE 1 Relative power of EEG under the new ratings of subjective response questionnaire (Mean ± SD)

		Relative power under the new ratings of acceptability of thermal environment			Relative power under the new ratings of thermal comfort			Relative power under the classification method A for thermal sensation		
EEG channel	EEG band	Ratings of the unacceptable thermal environment	Ratings of the acceptable thermal environment	% change	Ratings of being thermally uncomfortable	Ratings of being thermally comfortable	% change	Ratings of the Neutral-Slightly warm	Ratings of the Warm-Hot	Ratings of the Very hot
AF3	δ				0.581 ± 0.127	0.541 ± 0.126	−6.9%	0.520 ± 0.115^{B,C}	0.569 ± 0.130	0.629 ± 0.112
	θ									
	α							0.116 ± 0.036^{C}	0.105 ± 0.039	0.086 ± 0.030
	β							0.187 ± 0.069^{B,C}	0.157 ± 0.070	0.134 ± 0.064
AF4	δ							0.559 ± 0.104^{C}	0.597 ± 0.026	0.649 ± 0.106
	θ									
	α							0.110 ± 0.035^{B,C}	0.098 ± 0.035	0.084 ± 0.024
	β							0.162 ± 0.063^{B,C}	0.127 ± 0.054	0.123 ± 0.061
F3	δ				0.551 ± 0.137	0.507 ± 0.116	−8.0%	0.487 ± 0.095^{B,C}	0.531 ± 0.128	0.610 ± 0.158
	θ									
	α							0.124 ± 0.028^{C}	0.116 ± 0.037^{C}	0.078 ± 0.027
	β							0.191 ± 0.058^{B,C}	0.166 ± 0.064	0.135 ± 0.069
F4	δ				0.568 ± 0.130	0.522 ± 0.114	−8.1%	0.513 ± 0.103^{C}	0.545 ± 0.126	0.620 ± 0.129
	θ									
	α									
	β				0.142 ± 0.060	0.163 ± 0.058	14.8%	0.175 ± 0.054^{B,C}	0.148 ± 0.061	0.128 ± 0.063

(Continues)

TABLE 1 (Continued)

EEG channel	EEG band	Relative power under the new ratings of acceptability of thermal environment: Ratings of the unacceptable thermal environment	Ratings of the acceptable thermal environment	% change	Relative power under the new ratings of thermal comfort: Ratings of being thermally uncomfortable	Ratings of being thermally comfortable	% change	Relative power under the classification method A for thermal sensation: Ratings of the Neutral-Slightly warm	Ratings of the Warm-Hot	Ratings of the Very hot
F7	δ							0.566 ± 0.110[B,C]	0.616 ± 0.106	0.642 ± 0.096
	θ	0.152 ± 0.227	0.164 ± 0.032	7.9%	0.148 ± 0.023	0.156 ± 0.027	5.4%			
	α				0.092 ± 0.028	0.101 ± 0.037	9.8%	0.107 ± 0.035[B,C]	0.094 ± 0.033	0.082 ± 0.031
	β							0.164 ± 0.067[B]	0.133 ± 0.058	0.126 ± 0.065
F8	δ							0.582 ± 0.108[B,C]	0.630 ± 0.114	0.667 ± 0.087
	θ							0.159 ± 0.025[C]	0.151 ± 0.028	0.139 ± 0.022
	α							0.110 ± 0.040[B,C]	0.096 ± 0.038	0.084 ± 0.022
	β							0.150 ± 0.068[B,C]	0.111 ± 0.049	0.110 ± 0.054
FC5	δ							0.543 ± 0.113[C]	0.564 ± 0.122[C]	0.646 ± 0.118
	θ							0.159 ± 0.029[C]	0.153 ± 0.028[C]	0.133 ± 0.033
	α							0.111 ± 0.320[C]	0.106 ± 0.034[C]	0.083 ± 0.032
	β									
FC6	δ				0.598 ± 0.114	0.553 ± 0.107	−7.5%	0.538 ± 0.101[B,C]	0.579 ± 0.113	0.635 ± 0.084
	θ							0.163 ± 0.026[C]	0.155 ± 0.031	0.140 ± 0.027
	α							0.124 ± 0.040[C]	0.114 ± 0.039	0.091 ± 0.028
	β				0.135 ± 0.059	0.164 ± 0.068	21.5%	0.173 ± 0.063[B,C]	0.139 ± 0.053	0.114 ± 0.048

TABLE 1 (Continued)

EEG channel	EEG band	Relative power under the new ratings of acceptability of thermal environment			Relative power under the new ratings of thermal comfort			Relative power under the classification method A for thermal sensation		
		Ratings of the unacceptable thermal environment	Ratings of the acceptable thermal environment	% change	Ratings of being thermally uncomfortable	Ratings of being thermally comfortable	% change	Ratings of the Neutral-Slightly warm	Ratings of the Warm-Hot	Ratings of the Very hot
T7	δ	0.567 ± 0.126	0.519 ± 0.130	−8.5%	0.562 ± 0.128	0.517 ± 0.130	−8.0%	0.499 ± 0.126[C]	0.539 ± 0.131	0.610 ± 0.124
	θ							0.156 ± 0.033[C]	0.151 ± 0.031[C]	0.130 ± 0.034
	α	0.101 ± 0.035	0.115 ± 0.036	13.9%	0.103 ± 0.355	0.116 ± 0.356	12.6%	0.120 ± 0.033[C]	0.110 ± 0.037[C]	0.086 ± 0.035
	β									
T8	δ				0.551 ± 0.135	0.509 ± 0.119	−7.6%	0.491 ± 0.115[C]	0.532 ± 0.129[C]	0.621 ± 0.109
	θ									
	α				0.120 ± 0.044	0.135 ± 0.044	12.5%	0.140 ± 0.046[C]	0.127 ± 0.045[C]	0.099 ± 0.030
	β				0.158 ± 0.067	0.184 ± 0.067	16.5%	0.194 ± 0.069[B,C]	0.167 ± 0.035	0.128 ± 0.057
P7	δ	0.562 ± 0.131	0.511 ± 0.133	−9.1%	0.557 ± 0.127	0.509 ± 0.134	−8.6%	**0.471 ± 0.124[B,C]**	**0.536 ± 0.122[C]**	**0.639 ± 0.116**
	θ	0.150 ± 0.033	0.165 ± 0.029	10.0%	0.152 ± 0.033	0.166 ± 0.028	9.2%	0.173 ± 0023[B,C]	0.158 ± 0.030	0.137 ± 0.032
	α	0.107 ± 0.036	0.126 ± 0.041	17.8%	0.110 ± 0.038	0.126 ± 0.041	14.5%	**0.135 ± 0.042[B,C]**	**0.118 ± 0.038[C]**	**0.087 ± 0.030**
	β							**0.218 ± 0.008[B,C]**	**0.186 ± 0.072[C]**	**0.136 ± 0.063**
P8	δ				0.551 ± 0.144	0.504 ± 0.118	−8.5%	0.491 ± 0.121[C]	0.530 ± 0.131[C]	0.611 ± 0.107
	θ									
	α				0.123 ± 0.047	0.142 ± 0.047	15.4%	0.145 ± 0.053[C]	0.134 ± 0.048	0.105 ± 0.033
	β	0.150 ± 0.068	0.183 ± 0.066	22.0%	0.150 ± 0.062	0.186 ± 0.067	24.0%	0.194 ± 0.069[B,C]	0.165 ± 0.063	0.133 ± 0.055

(Continues)

TABLE 1 (Continued)

EEG channel	EEG band	Relative power under the new ratings of acceptability of thermal environment: Ratings of the unacceptable thermal environment	Ratings of the acceptable thermal environment	% change	Relative power under the new ratings of thermal comfort: Ratings of being thermally uncomfortable	Ratings of being thermally comfortable	% change	Relative power under the classification method A for thermal sensation: Ratings of the Neutral-Slightly warm	Ratings of the Warm-Hot	Ratings of the Very hot
O1	δ	0.547 ± 0.132	0.496 ± 0.120	−9.3%	0.547 ± 0.125	0.491 ± 0.121	−10.2%	**0.472 ± 0.104**^{B,C}	**0.521 ± 0.124**^{C}	**0.612 ± 0.131**
	θ	0.156 ± 0.034	0.167 ± 0.029	7.1%	0.157 ± 0.032	0.168 ± 0.030	7.0%	0.171 ± 0.026^{C}	0.162 ± 0.030	0.144 ± 0.030
	α	0.120 ± 0.044	0.140 ± 0.045	16.7%	0.120 ± 0.043	0.140 ± 0.044	16.7%	0.144 ± 0.046^{C}	0.133 ± 0.045^{C}	0.093 ± 0.032
	β	0.169 ± 0.072	0.192 ± 0.061	13.6%	0.167 ± 0.067	0.195 ± 0.061	16.8%	0.203 ± 0.060^{B,C}	0.179 ± 0.064	0.144 ± 0.074
O2	δ	0.524 ± 0.138	0.477 ± 0.118	−9.0%	0.533 ± 0.131	0.467 ± 0.114	−12.4%	**0.459 ± 0.114**^{B,C}	**0.501 ± 0.125**^{C}	**0.581 ± 0.133**
	θ				0.158 ± 0.031	0.171 ± 0.028	8.2%	0.174 ± 0.249^{B,C}	0.163 ± 0.029	0.148 ± 0.029
	α				0.137 ± 0.053	0.162 ± 0.052	18.2%	0.163 ± 0.054^{C}	0.151 ± 0.053^{C}	0.114 ± 0.039
	β				0.159 ± 0.060	0.195 ± 0.059	22.6%	0.204 ± 0.059^{B,C}	0.174 ± 0.059	0.149 ± 0.068

Note: For relative power under the new ratings of acceptability of thermal environment, and relative power under the new ratings of thermal comfort, only the channels that have significant differences are shown in the table. For relative power under the classification method A for thermal sensation, bold numbers indicate that all the channels that have significant differences. Coding: A - Neutral-Slightly warm, B - Warm-Hot, C - Very hot.

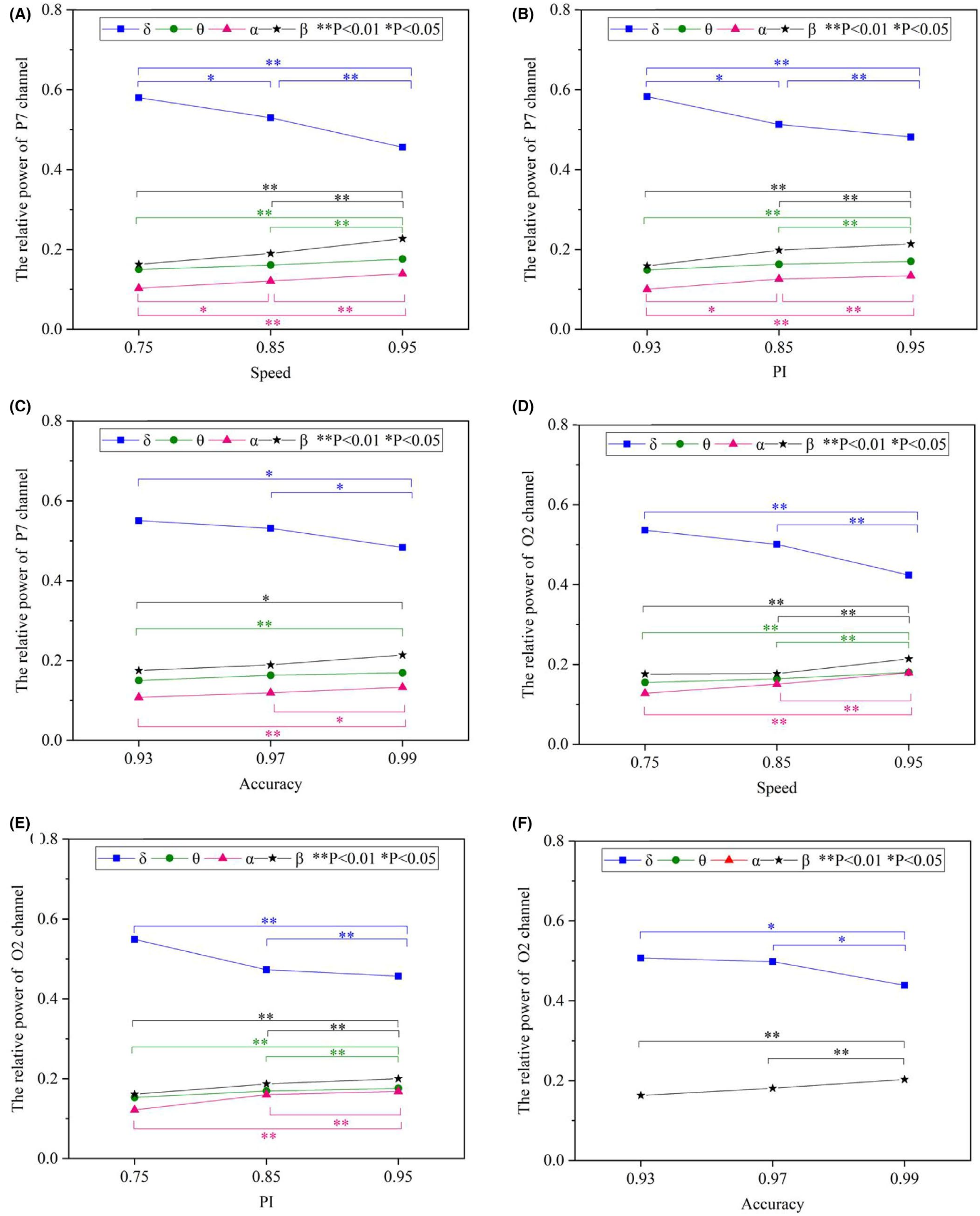

FIGURE 4 Relative power of EEG band for different index at which neurobehavioral tests were performed. (a) The relative power of the P7 channel for different speed at which neurobehavioral tests were performed. (b) The relative power of the P7 channel for different PI at which neurobehavioral tests were performed. (c) The relative power of the P7 channel for different accuracy at which neurobehavioral tests were performed. (d) The relative power of the O2 channel for different speed at which neurobehavioral tests were performed. (e) The relative power of the O2 channel for different PI at which neurobehavioral tests were performed. (f) The relative power of the O2 channel for different accuracy at which neurobehavioral tests were performed

TABLE 2 Potential channels and bands of EEG signals that can establish the relation between thermal comfort and EEG signals

EEG channel	EEG band	Acceptability of thermal environment	Thermal comfort	Thermal sensation	EEG channel	EEG band	Acceptability of thermal environment	Thermal comfort	Thermal sensation
AF3	δ		●		AF4	δ			
	θ					θ			
	α					α			
	β					β			
F3	δ		●		F4	δ		●	
	θ					θ			
	α					α			
	β					β		●	
F7	δ				F8	δ			
	θ	●	●			θ			
	α		●			α			
	β					β			
FC5	δ				FC6	δ		●	
	θ					θ			
	α					α			
	β					β		●	
T7	δ	●	●		T8	δ		●	
	θ					θ			
	α	●	●			α		●	
	β					β		●	
P7	δ	●	●	●	P8	δ		●	
	θ	●	●			θ			
	α	●	●	●		α		●	
	β			●		β	●	●	
O1	δ	●	●	●	O2	δ	●	●	●
	θ	●	●			θ		●	
	α	●	●			α		●	
	β	●	●			β		●	

Note: Coding: "●" means that band can be used to establish the relation with EEG signals.

TABLE 3 Relation between EEG and average speed at neurobehavioral tests were performed

Channel	Band	Intercept value	Slope value	R^2	p
P7	α	−0.031	0.17909	0.99993	0.005
O1	θ	0.05965	0.12308	0.99898	0.020
O2	α	−0.06474	0.25605	0.99611	0.036
F3	α	−0.0233	0.16464	1	0.001

strongest related to EEG signals, while in the case of cognitive performance, it was speed and PI. It was also observed that the EEG changes in the occipital lobe best described thermal comfort and cognitive performance. Especially, the P7 channel, O1 channel, and O2 channel in this lobe showed the best performance.

These results are compatible with Yao[44] and Horiba[45] on the relation between EEG and thermal comfort, both showing that changes in EEG signals can provide useful information for predicting thermal comfort ratings by humans. Kiyatkin[46] also showed that changes in brain temperature were similar to changes in EEG signals and that the thermal environment could act as a stimulus to affect them.

Table 1 shows significant differences for six channels, where the F7 channel belongs to the frontal lobe, T7 channel belongs to the temporal lobe, and the remaining four channels belong to the occipital lobe. The proportion of bands for which a significant difference was seen was 62.5% (5/8) in the temporal lobe and 87.5% (14/16) in the occipital lobe—the results implying the importance of the occipital lobe concerning subjective thermal responses. Emília et al[47] also reached a similar conclusion in their recent study. They found that the occipital lobe was more sensitive to the thermal environment than other cerebral lobes. As shown in Table 2, it can be intuitively found that the three channels belonging to the occipital lobe have the most potential for establishing relation between thermal comfort and EEG signals.

Present results show that the relative power of EEG is more likely to change significantly at high temperatures. In the study of Lv et al,[14] there were significantly higher EEG δ-band activities under the ambient temperature of 32°C compared with 25°C, and this is similar to the present results (Appendix S6). One plausible reason why the EEG signals changed significantly at high temperatures in the present study could be the heat acclimatization.[48,49] All subjects in the present experiments were sub-tropically acclimatized, so probably less sensitive to changes in the middle-temperature range studied. Lv et al[14] also found that the relative EEG power of δ-band changed at ambient temperatures. We also observed the same—only in the case of δ-band, statistically, significant differences were seen for 14 EEG channels.

Two classification methods, methods A and B, were used for the ratings of thermal sensation. To provide some verification of these classifications, we correlated the ratings with other responses that we believe could be detected by EEG changes, namely ratings of thinking clearly, fatigue, and the results of the Tsai-Partington test. Their selection was rationalized by the fact that EEG signals are related to sleep and thinking.[21] Table G in Appendix S9 shows the results for method A classification, and that trend was seen for the Tsai-Partington test result, not for the ratings of thinking clearly and fatigue. Table H in Appendix S9 showed the results for the classification method B and showed an additionally trend between fatigue and feeling warmer. No significant effects on the ratings of thinking clearly could be that the tests were made only 25 min into exposure where the workload could still be considered as low.[15] Details of these tests are in Appendix S10. It can be seen from Appendix S11 that under the same classification method used for the ratings of thermal votes, the mean skin temperature between different ratings also has significant differences, which further proves the credibility of the results of this study on the prediction of subjective thermal response by EEG signals.

It was observed that there was a strong relation between changes in EEG signals and speed and PI at which cognitive tests were performed, PI being the product of speed and accuracy at which tests were performed and thus most likely influenced by the speed. We did not see a strong relationship to accuracy. One reason also observed in other studies, for example, Wargocki and Wyon[50] and Lan et al,[51] is that the subjects pace the speed to ensure that no errors were performed.[42] Another explanation could be that the tests were performed early during exposure, and they were still motivated—highly motivated subjects can maintain the high performance for a short time under adverse thermal conditions. Finally, this could be due to acclimatization, which in the study of Angela et al[52] was claimed to allow students to maintain good grades at higher ambient temperatures.

Our results show that several channels detected significant differences in EEG channels for speed. These are α-band of P7 channel, θ-band of O1 channel, α-band of O2 channel, and α-band of F3 channel. They all could be considered to be EEG markers of speed. Table 3 shows the linear regression for these channels of EEG and speed. It is worth noting that three of the four channels, namely the P7 channel, O1 channel, and O2 channel, belong to the occipital lobe. This is consistent with our previous observation regarding the importance of the occipital lobe.

The measurements of EEG signals lasted only 30 min and were in the early stage of the exposure. This is a clear limitation of the present study. Furthermore, EEG signals could not be recorded separately when performing different neurobehavioral tests; however, different tests activate different brain regions.[53] Due to the limited number of samples in this study, the model for predicting thermal comfort with EEG signals has not been directly established, which is also a problem that needs to be addressed in the future research. The subjects were all acclimatized college students, which may not be representative of the entire population. It would be interesting to explore whether similar results could be observed for different subjects and other experimental conditions. Finally, we only recorded and analyzed 14 EEG channels and 4 EEG bands in this study, and we had to reduce the level of granularity on the scales recording subjective ratings of the thermal environment to observe significant relations. The results, therefore, need to be validated in separate experiments.

5 | CONCLUSIONS

This study explores the relation between the relative power of EEG signals, thermal comfort, and cognitive performance in neutral to hot environment. The main conclusions are as follows:

1. The relative power of EEG signals has a significant correlation with thermal comfort. The ratings of acceptability of thermal environment and thermal comfort are negatively correlated with the relative power of δ-band, but positively correlated with θ-band, α-band, and β-band. The ratings of thermal sensation have a better correlation with the relative power of the above four bands, but the correlation trend is opposite.
2. The relative power of EEG signals has a significant correlation with the performance of neurobehavioral tests. The speed, accuracy, and PI of completing the tests are negatively correlated with the relative power of δ-band, but positively correlated with θ-band, α-band, and β-band. Among them, the EEG signal has a better correlation with the speed of completing the test.
3. Compared with other lobes of the brain, the relative power of the EEG signals in the occipital lobe has a better correlation with thermal comfort and cognitive performance.
4. The relative power of P7 channel located in the occipital lobe is the most suitable as a single EEG channel to reflect joint thermal comfort and cognitive performance at high temperatures, especially its α-band.

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CONFLICT OF INTEREST

The authors declare they have no financial interests.

AUTHOR CONTRIBUTIONS

Xiaoyue Lang: Investigation (lead); Methodology (lead); Writing original draft (lead). Pawel Wargocki: Supervision (supporting); Writing-review & editing (lead). Weiwei Liu: Conceptualization (lead); Project administration (lead); Supervision (lead); Writing-review & editing (supporting).

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ORCID

Xiaoyue Lang https://orcid.org/0000-0002-8914-2237
Pawel Wargocki https://orcid.org/0000-0003-3865-3560
Weiwei Liu https://orcid.org/0000-0003-4314-0292

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