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Investigating the short-term cognitive abilities under local strong thermal radiation through EEG measurement

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ABSTRACT

Local Strong Thermal Radiant environment is widely present in industrial buildings, resulting in reduced cognitive abilities and thermal comfort for workers who perform monitoring operations. However, the effect is difficult to quantify, especially for jobs that are near hyperthermal radiant sources. In this study, ten young male subjects were directly exposed 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. Subjects were asked to perform cognitive tasks and subjective questionnaires and monitor 16 channels of EEG signals in a chamber. Based on the assessment of the EEG characteristics, the impacts of Local Strong Thermal Radiant on cognitive abilities and EEG are investigated. The results indicated that cognitive abilities were improved while the radiant temperature was below 250 °C. As the radiation temperature increases, the normalized power of β activity and α activity increases, and the vigilance and frontal EEG asymmetry increase. When it reaches 300 °C, all these features decrease and show an inverted "U" shape. The Local Strong Thermal Radiant arouses β activity and motivation for a short period and enhances cognitive abilities. The thermal comfort scores and thermal sensation scores rise with increasing temperature. Several international standards and literature can verify the findings of this study. This study's findings provided a foundation for assessing the cognitive abilities and inducing the mental states of hyperthermal radiant environment young workers to advance effective safety management in the industrial workshop.

1. Introduction

The thermal environment of a building affects people's physical, psychological, thermal comfort, and cognitive abilities [1–4]. According to function and usage, modern buildings are usually divided into civil and industrial buildings [5]. Most studies on the thermal environment of civil buildings focus on people's well-being, thermal comfort, and performance [6,7]. In industrial buildings, the thermal environment can be divided into high temperature and strong thermal radiant operations and high temperature and high humidity operations. In China, steel refining, steel rolling workshops in the metallurgical industry, casting, forging, and heating treatment workshops in the machinery manufacturing industry, and ceramic manufacturing workshops are characterized by a dry heat environment formed by high temperature and low humidity [8]. The indoor temperature with T_A exceeding 32 °C and T_W exceeding 25 °C can be considered a high-temperature environment [9].

1.1. Non-uniform thermal environment

The non-uniform thermal environments often originate from the asymmetric placement of heater sources, such as radiant heating systems in civil buildings and thermal radiation from workpieces in heating treatment workshops [8]. Different from using radiant panels for heating in civil buildings, many hyperthermal temperature workpieces exist in industrial workshops. These thermal environments are usually local, hyperthermal, and accompanied by strong thermal radiation, also known as Local Strong Thermal Radiant (LSTR). The worker's function is essentially operating to supervise, and establishing continuous monitoring becomes more challenging as a moment on task increases, with performance decrease continuing to increase [10]. Workers need to perform cognitive work in these places and make critical decisions under the thermal radiation environment and the dynamic potential risks. In

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Nomenclature

Abbreviations

EEG	Electroencephalogram
LSTR	Local strong thermal radiation
T_T	Thermal radiant panel's temperature
R_H	Relative humidity
T_A	Ambient temperature
T_W	Wet Bulb Globe Temperature (WBGT)
TSV	Thermal sensation vote
TCV	Thermal comfort vote
TAV	Thermal acceptance vote
V	Air velocity
NASA-TLX	National aeronautics and space administration task load index
PSD	Power spectral density
IEQ	Indoor environment quality
BMI	Body mass index
θ	Theta wave
α	Alpha wave
β	Beta wave
F_{TR}	Thermal radiation flux density
FEA	Frontal EEG asymmetry
ANOVA	Analysis of variance

addition, the hyperthermal radiation heat acts on the body surface and passes through the skull, affecting the nervous system such as the brain. These circumstances impact workers' cognitive abilities and performance, such as security, health, efficiency, and productivity.

According to the Design Code for Heating Ventilation and Air Conditioning of Industrial Building GB 50019 [11], the average surface temperature of electric radiant heating in civil buildings should not exceed 60 °C. However, in the industry building, some heater source temperatures can reach 1100 °C [12]. The four main parameters that determine the indoor thermal environment are air temperature, relative humidity, air velocity, and mean thermal radiant temperature [13]. WBGT (Wet Bulb Globe temperature) index is a fundamental indicator for comprehensively evaluating the thermal load of human exposure to the operating environment [8].

1.2. Current research status

Previous studies on non-uniform thermal environments were mainly based on thermal comfort and physiological parameters in civil buildings. Fanger et al. [14] noted that the asymmetry of radiation could generate local discomfort. Atmaca et al. [15] investigated the surface temperature of the radiant wall in the thermal comfort state is 44 °C. Wang et al. [16] explored the coupling of indoor ambient temperature and thermal radiant temperature on human thermal comfort in a non-uniform thermal environment and found that radiant temperature has a significant effect on mean skin temperature. The research on LSTR environments in industrial buildings is limited. Zhang et al. [17] focused on the workers' physiological responses and productivity in directed thermal radiation and proposed thermal radiation would aggravate and reduce productivity. Meanwhile, the asymmetrical thermal radiant primarily influenced the mean skin temperature and subjective thermal sensation [18].

These studies only utilized physiological responses, cognitive tasks, or subjective questionnaires, which are insufficient to quantify cognitive-vigilance status, which involves both brain responses and neuroscience [19]. Electroencephalogram (EEG) is a physiological and neuroscience approach that rapidly reflects the whole cortical and scalp surface electrophysiological activities [20]. Therefore, EEG is proposed to identify subjects' neurophysiological responses and cognitive abilities [21]. The EEG can monitor and record the brain's central nervous system and area rhythm activities [22]. Yao et al. [23] investigated the EEG responses and thermal comfort under different ambient temperatures and found that EEG global relative power of beta activities is predominant under the indoor temperature of 29 °C. Shan et al. [22] utilized the EEG to study the effects of various room temperatures on brain asymmetric activity and found that the frontal asymmetry was greatest under neutral conditions. Lang et al. [24] studied the influences of extreme high ambient temperature (39 °C) on EEG during a low intensity activity and found that the relative power of beta activities showed a declining tendency at 39 °C, which indicated that the high temperature could reduce cognitive performance. Choi et al. [25] investigated the impact of temperature on attention ability based on EEG and found that the lower attention level was in higher temperature conditions (PMV +2, +3).

Due to the significant differences between industrial and civil buildings, the current results regarding the effects of high temperatures on EEG and cognitive abilities in civil buildings require further research on whether they apply to LSTR environments. Compared to the subjective questionnaire-only approaches, the advantage of this method is that it can avoid the bias associated with subjective evaluations. Meanwhile, this method also partly elaborates and explains physiological mechanisms underlying changes in cognitive abilities. Limitations of this method: EEG equipment is expensive. Inability to perform large body movements and speak while using the EEG, as it can create many artifacts and affect the quality of EEG data. Meanwhile, increased sweating of personnel caused by higher temperatures and the potential for heat stress and heat stroke also influenced the exploration of higher temperatures. Therefore, this study aimed to investigate the effect mechanism of hyperthermal radiation on short-term cognitive performance and to find some critical temperature thresholds to protect workers from cognitive impairment, rather than to apply it to the shop floor for real-time monitoring.

1.3. The objectives of this study

Considering that LSTR is involved in radiant heating systems and daily heat treatment activities, more research is required to investigate the influences of the LSTR environment on humans to provide an effective physiological basis for cognitive variation in the LSTR environment. However, very few studies have reported the relationships among cognitive abilities, thermal comfort, and EEG on human subjects in the LSTR environment. Therefore, the main purpose of this study is to establish the interaction between human response and LSTR temperature. The primary objectives of this study were:

- To explore how the LSTR environment influences the human's cognitive abilities, EEG features, vigilance, and thermal comfort; and
- To investigate the most sensitive area and rhythm in human's EEG under LSTR environment; and
- To study the potential explanatory mechanisms of changes in cognitive abilities underlying the LSTR environment and practical contribution.

This study, which considering the cognitive abilities, EEG, thermal comfort, and motivation, provides us with a better understanding of the influence of LSTR environment.

2. Methodologies

2.1. Experimental facilities and conditions

All the investigations have been conducted at the Xi'an University of Architecture and Technology's climate chamber. The experiment was carried out in a room with a floor area of approximately 4.0 m^2 (2.0 m × 2.0 m, and the ceiling height is close to 3.0 m), the climate chamber in which T_T, V, and R_H can be adjusted. The location and layout of this climate chamber are shown in Fig. 1.

Two groups of electric high-temperature heat radiation boards were used as the heat source in the chamber to simulate a hyperthermal environment and LSTR. An adjacent room to the section was used for preparation work before experiments and as a resting area after the experiments. The temperature range of the electric high thermal radiant panel is from 100 °C to 300 °C with 50 °C intervals in this study.

In the hyperthermal radiant workshops, more heat radiation comes from directly in front of the workers [17,18]. Two groups of adjustable radiation boards were placed on the shelf directly in front of the participants to achieve a stable LSTR. To simulate the working environment of the workers in the hyperthermal workplace, the minimum safety distance was set at 0.8 m, based on the GB 10000–88(Human dimensions of Chinese adults) and GB/T 13547–92(Human dimensions in workspaces) [26,27]. The full length of the upper limb for the 95% percentile adult male is approximately 0.8 m. The heat source panel used four high thermal radiant electric tubes with an input power of 4000W. An early our filed study of a hot rolling plant in Xi'an was carried out to simulate the real Local Strong Thermal Radiant environment. In the actual hyperthermal radiant workshop, some heat sources surface temperature: cooling bed (100–300 °C) and packaged steels (140–150 °C). The cooling bed area is the largest and is the region that dissipates more heat. In addition, the 50 °C interval already makes a difference and distinction to thermal sensation and cognitive abilities. The higher temperatures are not permitted because this can lead to heat discomfort, heat stroke, and heat stress [28]. Meanwhile, sweat artifacts caused by sweating can affect the quality of the EEG signal. In this study, five grades of radiation temperature were established and designed to achieve equally spaced thermal radiant temperature, as listed in Table 1. Two temperature, humidity, and wind speed probes are placed next to the subject to continuously measure the temperature and humidity around the subject. Furthermore, an alert system was implemented in the chamber to prevent the equipment from malfunctioning.

2.2. Measurement and instruments

Actual T_A, R_H, V, and T_W were monitored utilizing Testo - Smart Probes and WBGT indicator devices (Table 2). The apparatuses were situated at the center of the room and near the participants at the height of 1.1 m. The neck and head postures of participants in the seated position correspond to 1.1 m [17]. Moreover, these devices were placed near the body areas sensitive to thermal conditions, and the data were collected every 10 s. The temperature and humidity ranges of these instruments are −20 °C ∼ +60 °C and 0–100%, with accuracies of ±0.5 °C and ±2%, respectively.

Table 1
Setting the parameters of each experiment session.

Variables	T_R	Cognitive task	R_H	Distance
Range	100 °C 150 °C 200 °C 250 °C 300 °C	Agility test Memory test Calculation test Searching test	10%–20%	0.8 m

Table 2
Parameters of devices.

Type	Name	Measuring devices	Versions	Range
Environmental parameters	T_A R_H V	Testo-Smart Probes	405i	−20 °C ∼ +60 °C 0–100% 0–30 m/s
	T_W	WBGT index meter	2006	5–40 °C
Physiological indices	EEG	EEG device	Open BCI	128 Hz 16 Channels

2.3. Participants

The sample size was determined according to statistical power and effect size in this study, which used a counterbalanced within-subject design [29]. According to the previous studies, the statistical power and effect size of the F-test was calculated using G*power-3.0 software [17,29]. In addition, the sample size of some related literature varied from 7 to 14 [25,30,31]. Therefore, ten participants can provide enough statistical power to identify differences. Ten ($n = 10$, statistical power $= 0.8274 > 0.8$, effect size $= 0.8$) male volunteer students participated in the study and were offered monetary rewards to improve their motivation. Female participants were excluded from this investigation because the menstrual cycle may affect thermal comfort and other

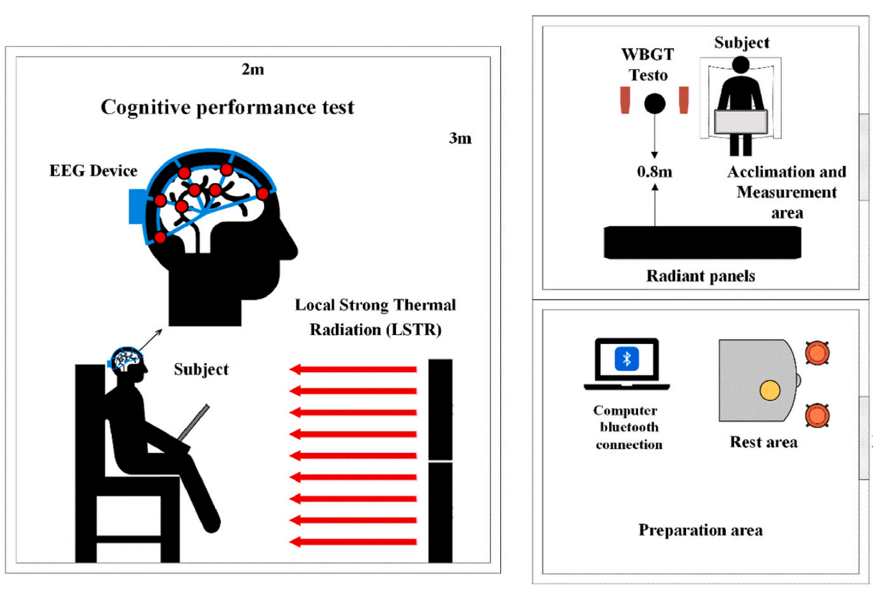

Fig. 1. Location and layout of the climate chamber.

results, while the duration of the research lasted longer than one month [25]. In addition, the main members of the heat treatment workshop for high-temperature radiation are males [12]. The ten participants were divided into five groups, each of two participants. The mean age, weight, height, and BMI of all participants were 21.4 ± 1.9 years, 70.41 ± 6.1 kg, 1.75 ± 0.04 m, and 22.48 ± 1.04 kg/m^2, respectively. The experiment included five different temperature conditions, and each subject was exposed to all five temperature levels. Therefore, individual differences could be counteracted more effectively [32].

These participants have lived in Xi'an (34°16' N, 108°54' E) for over two years and have acclimated to the climate in Shaanxi. The average outdoor temperature in winter is −1.5 °C. During summer, the mean temperature is 26.3 °C. The relative humidity was 60 ± 10% [33]. Pre-experimental enough training was executed to minimize the effects of unfamiliarity with the investigation and learning effects [34]. Before one week of the experiment, the subjects practiced the experimental procedures and cognitive tasks at least 10 times in the climate chamber without thermal radiant. The condition during this pre-experimental is the ambient temperature (26 °C). On each day, there were two timeslots, i.e., 9:00 a.m.–11:00 a.m., and 3:00 p.m.–5:00 p.m. The two subjects in each group were randomized to either morning or afternoon for the first experiment, but the subsequent four experiments had the same period (9:00 a.m.–11:00 a.m. or 3:00 p.m.–5:00 p.m.) as the first to minimize the effect of work habits or biological clocks [35]. The Latin-square design is a within-subject experimental design strategy commonly employed in human research to reduce tiredness induced by sequential effects and their proficiency [36]. Table 3 is a five-by-five balanced design experiment sequence using the Latin-square method. Each group was separated by 5 days between two experiments. According to the ASHRAE Standard 55 [37], the clothing insulation was calculated to be 0.8 clo according to the thermal resistance of clothing data with additional insulation of the chairs (0.05clo); thus, the overall clothing insulation was 0.85clo. The metabolic rate was configured as sedentary (1.2 met) [38]. The participants were instructed to continue with their tasks before they could not tolerate the LSTR environment. To mitigate the effects of the Hawthorne effect [39], subjects were told that their experimental performance would be anonymized. All subjects completed experimental sessions.

2.4. Cognitive performance test battery

This study adopted four different content and similar difficult mental tasks to measure participants' cognitive performance: agility, memory, calculation, and searching. These programs are based on neurobehavioral tests and cognitive resource allocation, which are the most frequently utilized to evaluate neurocognitive processing [40,41]. One short test on the tablet was selected for each task, and the task completion time and the number of errors will be recorded and analyzed. We quantified subjects' performance (productivity, intelligence level, and cognitive ability) on the task by the average completion time and the number of errors in the trials, the picture as shown in Fig. 2. A detailed description of each task is presented below.

Task 1 - Agility test (hand-eye synergy): Participants are required to find other letters or patterns hidden in the same letter. Errors increase by one when the same letter is clicked (Fig. 2(a)). A total of 15 letter sets were found in the project. Finally, the completion time of the item and the number of errors were recorded.

Task 2 - Memory test: An 8-digits memory simulation information and acquisition task to characterize the current memory cognitive ability. The subjects had 10 s to memorize the numbers and write them down repeatedly on the tablet screen within 10 s. Any digit error increments the item's error count by one (Fig. 2(b)). A total of 15 sets of numbers were memorized in the project. Finally, the completion time of the item and the number of errors were recorded.

Task 3 - Calculation test: Four mixed operations of one-digit numbers simulate some numerical computing problems and characterize the current computational cognitive ability. The results are listed as four options, one of which is the correct answer. When the calculation is wrong, or the wrong choice is made in a hurry, the item will be incorrect, and the number of errors will increase by one time, and the subject needs to calculate 15 groups of this type of question (Fig. 2(c)). Finally, the completion time of the item and the number of errors were recorded.

Task 4 - Searching test: The subjects need to click the numbers in order from small to large. These numbers are not continuous, their positions are randomly distributed, and the size of the numbers is also randomly generated. When the numbers are not clicked out in ascending sequence, the item will create an error, and the number of errors will increase by one, and the subject needs to finish 15 groups of this type of question (Fig. 2(d)). Finally, the completion time of the item and the number of errors were recorded.

Table 3
Experiment sequence using balanced Latin-square method.

	Experiment sequence				
G1	D1 300 °C	D6 250 °C	D11 150 °C	D16 200 °C	D21 100 °C
G2	D2 200 °C	D7 300 °C	D12 100 °C	D17 150 °C	D22 250 °C
G3	D3 100 °C	D8 150 °C	D13 300 °C	D18 250 °C	D23 200 °C
G4	D4 150 °C	D9 200 °C	D14 250 °C	D19 100 °C	D24 300 °C
G5	D5 250 °C	D10 100 °C	D15 200 °C	D20 300 °C	D25 150 °C

Note: G represents five participant groups, and D represents the twenty-five days of the experiment.

2.5. Questionnaire and survey

The questionnaires exploited to explore subjective opinions and perceptions were assembled from ASHRAE Standard 55 [37] and other research [17,42]. The questionnaire is composed of two main sections: (1) Basic information, which includes the name, height, weight, and age, etc. (2) The comprehensive questionnaires, which include surveys on indicators such as TSV, TCV, TAV, motivation, and NASA-TLX. The thermal sensation is a subjective representation of the environment that is influenced by psychological and physiological responses [18]. The thermal sensation questionnaires in this research utilized a 7-point continuous scale to evaluate different layers of the LSTR environment. The thermal comfort was cast on a 4-point numerical scale to assess. Thermal acceptance is acceptable (1) and unacceptable (−1). Motivation is the spiritual power and passion of workers to perform their work. If an individual is not interested in working, his productivity should decrease, no matter how precisely his performs [43]. The motivation utilized a 7-point scale to evaluate. The NASA TLX is a subjective workload evaluation application that enables users to perform subjective workload assessments on operators working with various human-machine interface systems [44]. To rate the subject's mental load easily and quickly, these six subscales generate a workload score scale from 0 to 100. The subjects were told before the experiment that the weight (importance level) and the score of each subscale should be considered at the same time, and finally, the score of each subscale was obtained [45,46]. The higher the score is, the greater the mental workload is. Further descriptors can be found in Fig. 3.

2.6. Experimental protocol

A graphic figure of the participant experimental framework is described in Fig. 4. The whole study was performed in the winter, from December 6th to 30th, 2020. The total duration of each experiment was 120 min, including 30 min of pre-exposure preparation (in the

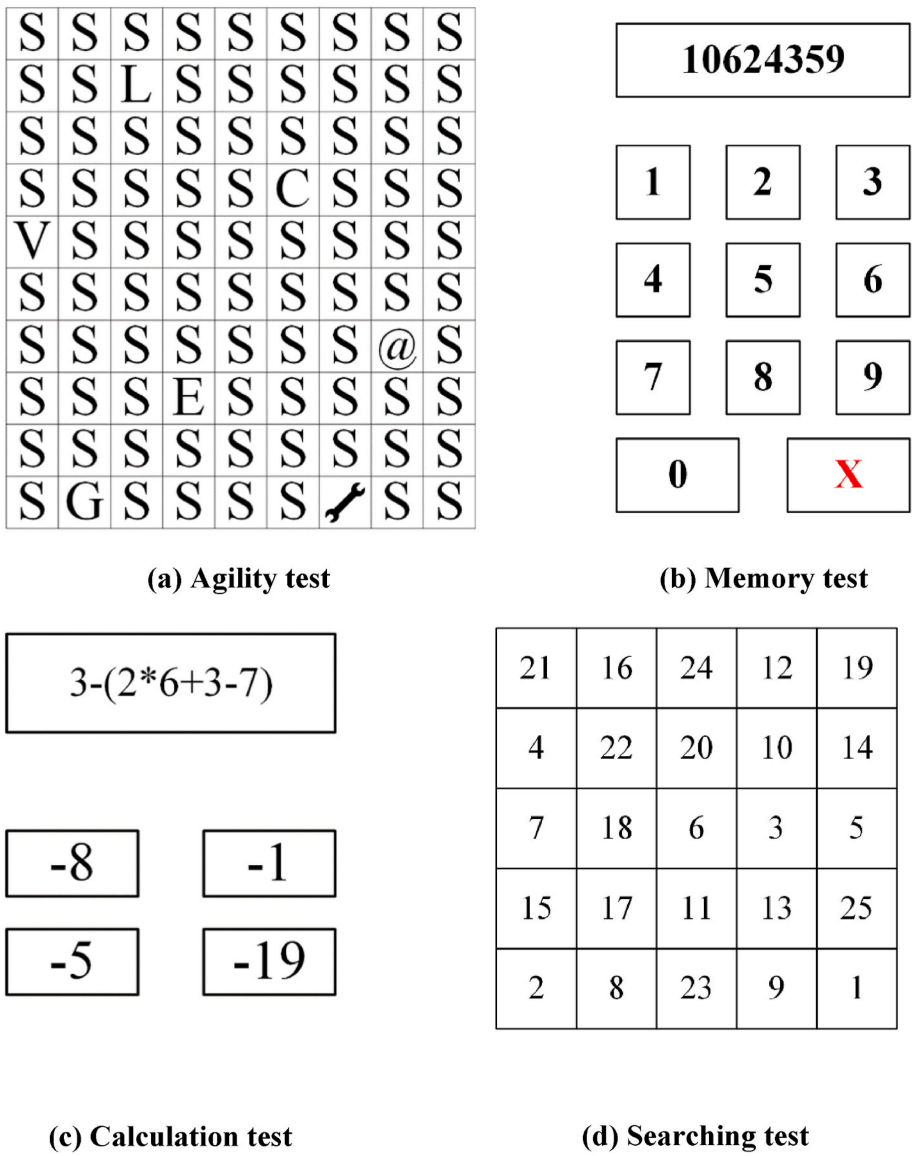

Fig. 2. Four cognitive tasks.

preparation area), 60 min LSTR exposure (30 min acclimatization + 20 min cognitive task + 10 min questionnaire, in the measurement area), and 30 min rest (in rest area). The entire LSTR exposure procedure for each condition lasted for 60 min. In the preparation area, participants were asked to wash their hair and blow-dry. Then, they were informed of the protocol and the possible hazards of the experiment. Subsequently, the subjects signed informed consent forms. The subjects require to wear an EEG cap and adjust it to stabilize the EEG amplitude before the start of the exposure experiment. In the measurement area, the hyperthermal radiant panel was opened at 0 min and set the radiant temperature to the expected temperature (100 °C–300 °C) to maintain a hyperthermal temperature environment. Meanwhile, the participants were requested to sit in the measurement area for 30 min as an acclimatization period to stabilize the physiological parameters after arriving at the measurement chamber [18]. In the cognitive task, EEG cap was opened to measure the EEG signals of participants. To acquire the high-quality signals, subjects were instructed to observe the following guidelines before and throughout the experiment: (1) have a good rest at night and adequate drinking water before the experiment. (2) subjects were prohibited from talking and moving their limbs significantly during the experiment to ensure data stability. (3) the continuous 20 min of data collection of EEG start to be conducted only if these signals are appropriate and normal. After 20 min of cognitive task, a 10 min questionnaire needs to be completed and submitted. The experiment was conducted 3 h after the meals to reduce the effect of hypoglycemia on the experiment. The participants could leave the measurement area for the rest area once they had completed the procedure. After the experiment, 50 records of EEG data sequences were acquired from the ten participants. The experiment protocols were performed following the tenets of the Declaration of Helsinki [47] and informed consent was obtained from each subject.

2.7. EEG basic information

As discussed previously, EEG provides a constant and precise mental state assessment in the laboratory. This brain activation can be explained by EEG rhythms, including delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (>30 Hz) frequency ranges. The delta frequency band is dominant during deep slumber, and the theta frequency band is associated with statuses such as tiredness, inventive enlightenment, and contemplation. The alpha frequency band is involved in ease and relaxed condition whereas the beta frequency

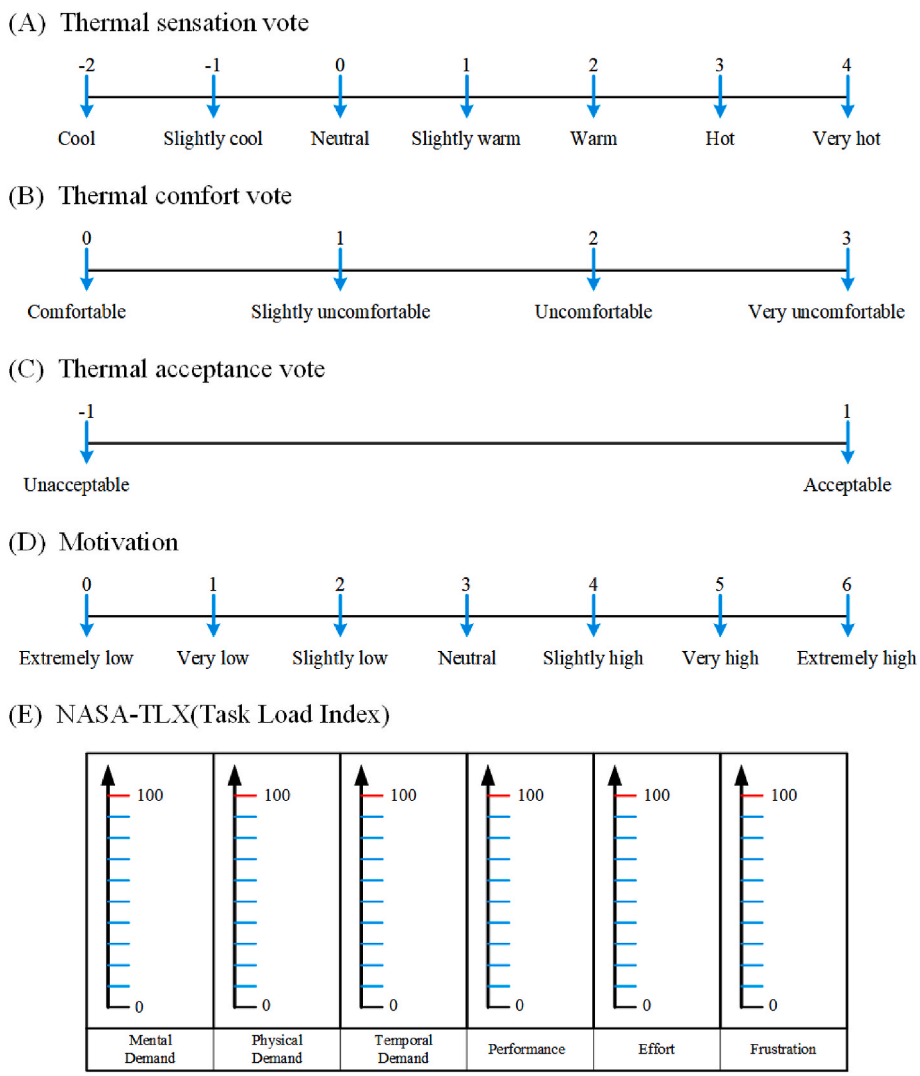

Fig. 3. Comprehensive questionnaire.

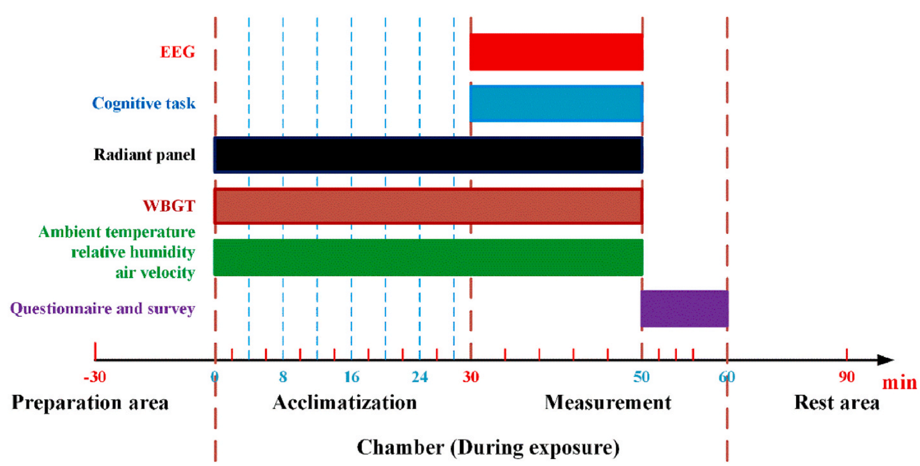

Fig. 4. Experiment procedure.

band is predominant during vigilant, positive states, as well as a matter of concern, and the gamma frequency band is characterized by high intellectual states and executive function [22].

Furthermore, location in the head relates to various brain functional responses. The frontal lobe of the brain, for example, is recognized as a mood and perception control center. A parietal lobe coordinates nerve impulses associated with senses and linguistic processes, whereas a temporal lobe is an entire organization of sensory information. Therefore, modern EEG equipment, especially wearable EEG monitors, contains numerous electrodes that can be placed on various regions of the head, and bilateral mastoids were used as reference electrodes. In this research, data collection and transmission utilize wireless Bluetooth technology. [Fig. 5(a) depicts various brain activations in different locations, and Fig. 5(c) records brain activation caused by changes in cognition. For example, electrodes positioned in the frontal region [e.g., AF3, AF4, F7, F8, F3, F4].

2.8. EEG data preprocessing

EEG signals are hailed as the "golden indicators" for efficacy evaluation because they can accurately reflect changes in the brain's state [20]. The EEG signal is weak, its amplitude range is below 100 μV, and the signal-to-noise ratio is low [21]. This causes some artifacts (mainly eye movement artifacts produced by blinking and eyeball rolling, sweat artifacts usually appear in the hyperthermal environment) to greatly impact the experimental results, and it is necessary to preprocess the collected EEG data.

The EEG signals were measured by the OpenBCI electrode cap (OpenBCI Inc.) at a sampling frequency of 128Hz in real-time. The impedance between electrode and scalp was maintained at less than 5 KΩ. The conductive paste is filled between the electrode and scalp to stabilize the EEG signals. The Open BCI GUI software recorded the signals. Despite the use of conductive paste, the quality of EEG signals can be affected by sweat produced in response to hyperthermal radiation stimulation. These sweat artifacts are slow-frequency artifacts, which frequency usually is 0.25–0.5Hz [48].

The offline EEG data were preprocessed by the widely used MATLAB 2020(MathWorks, Natick, Massachusetts, USA) with a plug-in EEGLAB toolbox (version 2020.0), and bilateral mastoids were used for re-reference. The data were re-referenced using a common average reference and detrended [49]. In this study, low-frequency noises (4.0 Hz and lower) and high-frequency noises (30.0 Hz and higher) were eliminated through the hamming windowed sinc finite impulse response (FIR) digital filter [50]. The sweat artifacts can be filtered and some of the more exaggerated data is required to be removed [24]. Meanwhile, the higher radiant temperature experiments ($T_T > 300$ °C) were not performed. The eye movement and blinking artifacts were separated using independent component analysis (ICA), and the IC Label plug-in was used for artifact calibration and removal [51].

2.9. Mental workload state measurement

EEG for representing brain activities has been efficiently employed to comprehend varied levels of mental workload status with remarkable correlation with EEG power. (i.e., the quantity of the signal energy per unit time). The EEG data analysis involves the calculation of PSD for the frequency bands. These bands can be utilized to recognize and categorize cognitive processes such as mental workload, cognitive abilities, executive functions, performance, and memory.

2.9.1. Power spectrum features

The power spectrum feature is widely used in EEG feature extraction. Usually, spectral analysis of the sampled data is performed with a PSD method based on the Fast Fourier transform [23]. After being sampled, the dataset underwent a windowing (Hamming) to minimize spectral leak, then calculated by a Fourier-based PSD estimation, *P (f)*, of the

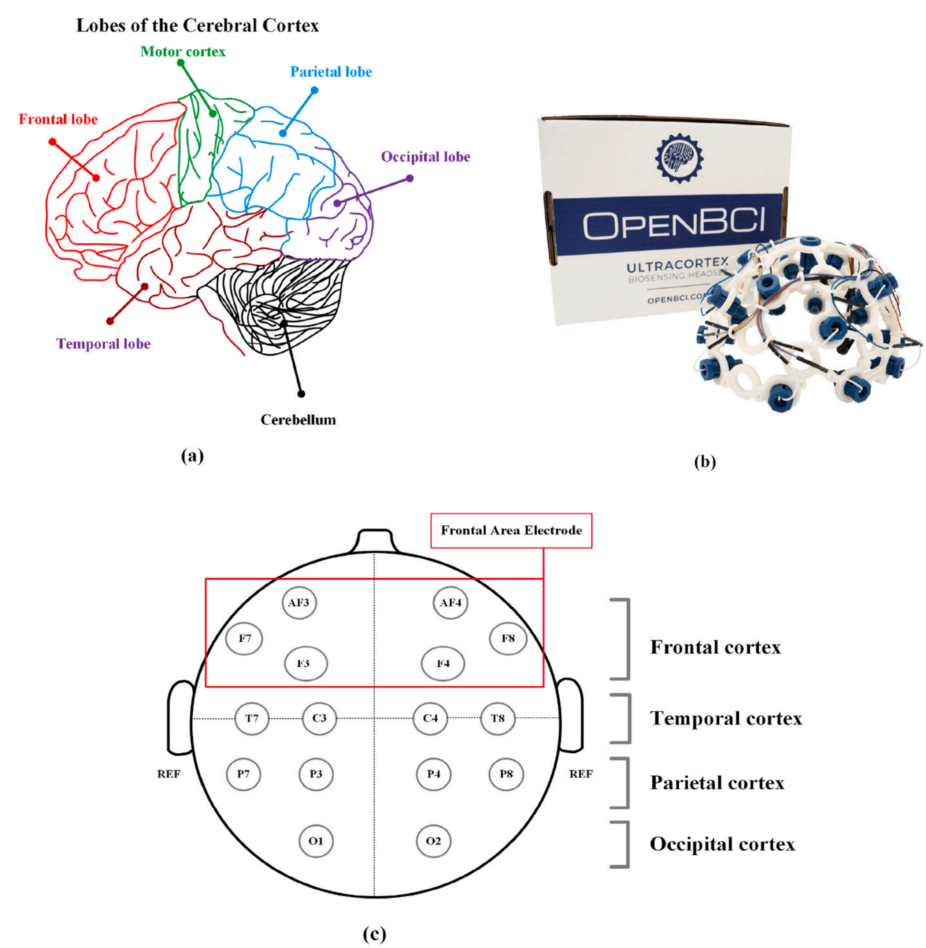

Fig. 5. Briefly of wearable EEG equipment (a) Lobes of the cerebral cortex; (b) Wearable EEG cap; (c) Electrode channels in four cerebral cortexes (i.e., AF3, F7, F3, T7, C3, P7, P3, O1, O2, P4, P8, C4, T8, F4, F8, AF4, the REF is the reference electrodes).

resampled discrete-time sequences *s(t)*:

$$P(f) = \frac{1}{N\Delta\tau}\left|\Delta\tau\sum_{k=0}^{N-1} s(t)e^{-j2\pi fk\Delta\tau}\right| \tag{1}$$

Where the $\Delta\tau$ denotes the sampling interval, and it is the reciprocal of the sampling frequency. Based on the Welch method, the Hamming window function is employed to calculate the PSD of the EEG signal, as shown in formula (1). Then, the PSD [ms^2/Hz] is calculated, and the interesting rhythms' power is calculated by integrating their bands. The power spectrum analysis was performed using the normalized power spectrum (also known as relative power) to reduce the differential effect between different subjects [1,23,24,52]. The normalized power spectrum method is introduced as follows:

$$P_{nor} = \frac{P_i}{\sum_{i\in(\theta,\alpha,\beta)} P_i} \tag{2}$$

Where *Pi* represents the absolute average power of each rhythm. The normalized power spectrum is the ratio of each band's power to the sum of the three bands (θ, α, β).

2.9.2. Vigilance and arousal

The increase of the theta rhythm band, whereas the decrease of the alpha rhythm band demonstrates the brain's conversion from wakefulness to resting states. Beta rhythm is correlated with concentration, vigilance tension, and nervousness [53]. The indicators of arousal and vigilance are calculated to quantify the mental workload and cognitive abilities using the EEG frequency band powers:

$$V = \frac{P_\beta}{P_{(\theta+\alpha)}} \tag{3}$$

2.9.3. Frontal EEG asymmetry

According to the previous studies of asymmetrical brain activities indicated, it is believed that the left hemisphere of the brain is more associated with aggressive and positive, and the right hemisphere of the brain is more correlated with frustrated and negative [22]. The FEA methods show the level of activation in the left and right areas to quantitatively indicate mental state by contrasting the PSD in the alpha and beta frequency scope between these two regions. Similarly, the greater the calculated value, the higher the degree of arousal of the individual. The specific calculation formula is shown in (4).

$$FEA = \frac{P(AF3+F7+F3)_\beta}{P(AF3+F7+F3)_\alpha} - \frac{P(AF4+F8+F4)_\beta}{P(AF4+F8+F4)_\alpha} \tag{4}$$

2.10. Statistical analysis

After ensuring that the data were normally distributed (Shapiro -Wilk's-W-test) and homogeneity of variance test (Levene's test) [54], we first calculated the influence of environmental status on physiological and psychological indicators were analyzed by utilizing one way repeated-measurement ANOVA with thermal radiation temperature as the factor. One way repeated-measurement ANOVA can effectively control the effect of individual differences on experimental results. The Mauchly's test of sphericity to determine whether the data meets the assumption of sphericity. If not, the degrees of freedoms were corrected utilizing Greenhouse-Geisser. Post hoc multiple comparisons between the conditions in every group were executed utilizing the Bonferroni correction to identify whether the effect of thermal radiation temperature was significant. Statistical significance was defined as $P < 0.05$. Not normally distributed data were analyzed using the Wilcoxon Matched Pairs Test. In addition, the effect size, which guarantees the credibility of difference between the groups in case of a lack of samples, was calculated in this study. According to Cohen's psychological studies [55], the effect size of the repeated-measurement ANOVA can be calculated as η^2(partial Eta squared) in SPSS, which is usually represented as the ratio of the standard deviation between the groups and the standard deviation within the group. $\eta^2 > 0.01$, $\eta^2 > 0.06$, $\eta^2 > 0.14$ represent small, medium, and large effect sizes, respectively [1]. The statistical power also be calculated utilizing General Linear Model in SPSS (observed power) [29]. When the observed power is greater than 0.8, the current sample size is sufficient to detect difference [56]. The analyses were performed using SPSS 22.0 software (IBM, New York, NY, USA) and Origin Pro software 2021 (Origin Lab, Massachusetts, USA.).

3. Results

3.1. Environmental parameters

The influence of radiation temperature factors on ambient temperature should be considered. The ambient temperature data were obtained for 60 min with 10 s intervals and averaged for each subject at each temperature condition. The WBGT temperature measured simultaneously was compared and analyzed to get the current indoor state. The airspeed did not change significantly for different ambient temperature patterns ($P > 0.05$). In addition, the change of real relative humidity at different temperatures was measured and controlled within a certain range (mean ± standard deviation), respectively, which ensures that the change of mental load is caused by the single factor of thermal radiation temperature ($P > 0.05$). Table 4 describes the measured environmental factors in the different thermal radiant temperatures. The thermal radiation flux density is the net thermal radiant heat flux to human body [57].

When the T_R varies in the range from 100 °C to 300 °C in Fig. 6, the T_W and T_A increase with the T_R. After the T_R exceeds 200 °C, the T_W exceeds 29 °C, and the T_A reaches 32 °C. As the T_R rises, the T_W and the T_A reach high temperatures ($T_W > 25$ °C, $T_A > 32$ °C). At 250 °C and 300 °C, the subjects were exposed to high temperatures and strong thermal radiation. The detailed one way ANOVA and Bonferroni post hoc multiple comparisons results was in Appendix A. (T_W: $P_{sphericity} = 0.340 > 0.05$, $F = 712.41$, $P < 0.001$, $\eta^2 = 0.988$, Observed power = 1; T_A: $P_{sphericity} = 0.185 > 0.05$, $F = 818.42$, $P < 0.001$, $\eta^2 = 0.989$, Observed power = 1). $P_{sphericity}$ is the significance of Mauchly's test of sphericity.

3.2. Cognitive task performance

The mental cognitive task completion time and the number of errors can directly reflect the current state of mental workload. Task completion time: There are significant differences in the completion time of the tasks ($P_{sphericity} = 0.344 > 0.05$, $F = 15.625$, $P < 0.001$, $\eta^2 = 0.635$, Observed power = 1) under the five thermal radiant temperatures. It can be observed that the task completion time decreased when the T_A varied from 100 °C to 300 °C. The Bonferroni with pairwise comparisons results is shown in Fig. 7(a). This is likely because the subjects' performance was stimulated by the thermal radiant.

The number of errors: There are significant differences in the number

Table 4
Environmental parameters under different thermal radiation temperatures.

T_R	100 °C	150 °C	200 °C	250 °C	300 °C
	Mean ± Standard deviation				
T_W/(°C)	20.10 ± 0.49	23.87 ± 0.58	29.01 ± 0.92	32.34 ± 0.54	33.60 ± 0.91
T_A/(°C)	23.00 ± 0.53	26.89 ± 0.99	31.82 ± 0.60	35.49 ± 0.85	37.68 ± 0.64
R_H/(%)	17.5 ± 1.7	16.1 ± 2	12.9 ± 2.7	11.4 ± 1.3	10.5 ± 1.5
F_{TR}/(kW/m^2)	0.19	0.32	0.55	0.75	1.1

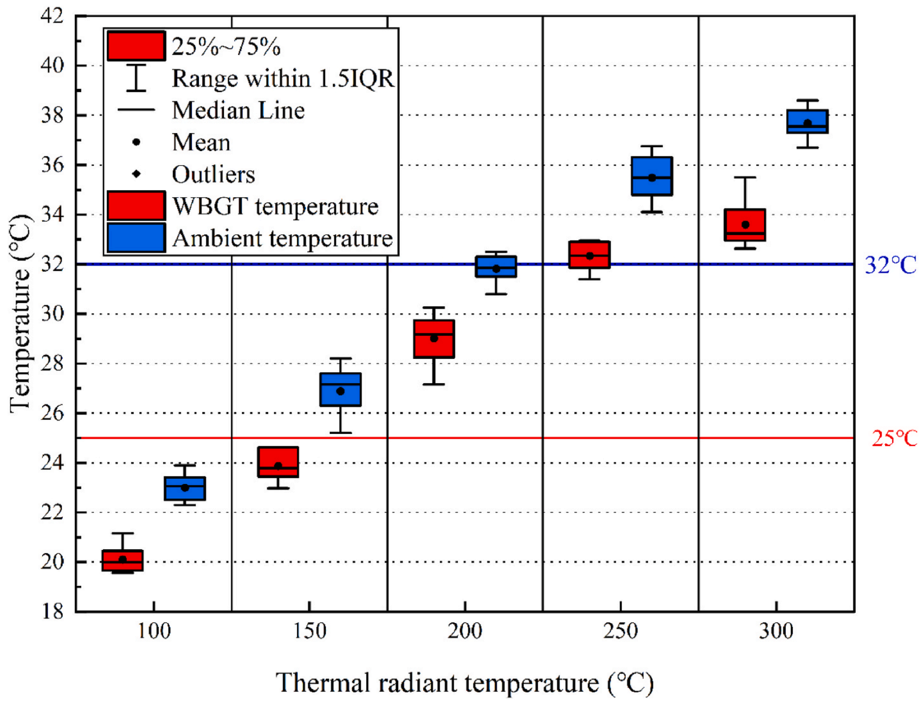

Fig. 6. WBGT temperature and ambient temperature.

of errors in the tasks under the five thermal radiant temperatures ($P_{sphericity} = 0.285 > 0.05$, $F = 50.831$, $P < 0.001$, $\eta^2 = 0.850$, Observed power = 1). It can be observed that the number of errors firstly decreased and then increased with 250 °C as an inflection point. On average, the optimum performance was at 250 °C, and the further the radiation temperature away from 250 °C, the worse the performance. Participants commonly achieved their greatest performance at 200 °C and 250 °C. In addition, the relationship between cognitive performance and the thermal radiant temperature was confirmed to be significant as a U-curve. This suggests that the high thermal radiant temperature has significantly affected the cognitions of some participants, their endurance of the physical arrived at the final stage. The Bonferroni with pairwise comparisons results is shown in Fig. 7(b).

3.3. Subjective questionnaire survey

The subjective questionnaire survey scores of different thermal radiant temperature conditions are described in Fig. 8. It can be observed that the motivation ($P_{sphericity} = 0.195 > 0.05$, $F = 35.054$, $P < 0.001$, $\eta^2 = 0.796$, Observed power = 1) firstly shows a statistically significant increase when the T_A varied from 100 °C to 250 °C, then dropped at 300 °C. The subjects subjectively think that motivation is reduced under high temperatures. TAV ($P_{sphericity} = 0.485 > 0.05$, $F = 18.614$, $P < 0.001$, $\eta^2 = 0.674$, Observed power = 0.99) is decreased trend, and they prefer a cool environment. When the test task is the same, the TSV ($P_{sphericity} = 0.904 > 0.05$, $F = 61.475$, $P < 0.001$, $\eta^2 = 0.872$, Observed power = 1) and TCV ($P_{sphericity} = 0.563 > 0.05$, $F = 114.451$, $P < 0.001$, $\eta^2 = 0.927$, Observed power = 1) show an upward trend, indicating that the subjects are more sensitive to high temperatures and feel hotter. There are significant differences in the questionnaire scores. From the questionnaire, the workers reached the thermal comfort at 100 °C; many workers felt hot (+3) to very hot (+4) in 250 °C and 300 °C due to heat discomfort, more than 60% were thermally unacceptance in 250 °C, and reported discomfort (+2) from 200 °C. The 300 °C was deemed as very hot (+4), very uncomfortable (+3), and unacceptable (−1). The motivation reaches its maximum as 200 °C and 250 °C.

The variation of load index at different thermal radiant temperatures is shown in Fig. 9. There is a significant increase in NASA-TLX scores with the rise of thermal radiant temperature. The higher the temperature, the higher the corresponding scores from the subjective perspective for these six subscales. Mental demand is the most influential to their cognitive performance, whereas they consider physical demand the least influential. This is likely because they sit in the chairs for cognitive tasks and questionnaires. Compared to lower thermal radiant temperatures, participants in a hyperthermal radiant environment require greater effort to resist the heat. Meanwhile, they suffer more physical and mental frustration. Table 5 describes the effect size and observed power of NASA-TLX in the different thermal radiant temperatures. The detailed one way ANOVA and Bonferroni post hoc multiple comparisons results was in Appendix A.

3.4. EEG features calculation

3.4.1. Normalized power

Based on the proceeded EEG data, the three interested rhythms' power (i.e., theta, alpha, beta) is evaluated by integrating the respective bands (after the normalization). It can be seen from Fig. 10 that the theta activity ($P_{sphericity} = 0.716 > 0.05$, $F = 15.670$, $P < 0.001$, $\eta^2 = 0.635$, Observed power = 1) after conversion does not change much at each radiation temperature, and it decreases slightly at 200 °C and 250 °C. There is an evolutionary increase in alpha activity ($P_{sphericity} = 0.354 > 0.05$, $F = 8.326$, $P = 0.008$, $\eta^2 = 0.481$, Observed power = 0.841) as the thermal radiant temperature rises. Moreover, the beta activity reaches its maximum value at 250 °C. Then, the beta activity appears downward again at 300 °C. Combining the tendency of these three frequency band powers indicates that as the radiation temperature rises, fast waves (beta activity) ($P_{sphericity} = 0.176 > 0.05$, $F = 8.889$, $P = 0.001$, $\eta^2 = 0.497$, Observed power = 0.998) are produced in a large amount in the body, and more emotions such as excitement are generated. The detailed one way ANOVA and Bonferroni post hoc multiple comparisons results was in Appendix A.

3.4.2. Vigilance and arousal

There were statistically significant differences in vigilance ($P_{sphericity} = 0.116 > 0.05$, $F = 40.394$, $P = 0.001$, $\eta^2 = 0.818$, Observed power = 1)

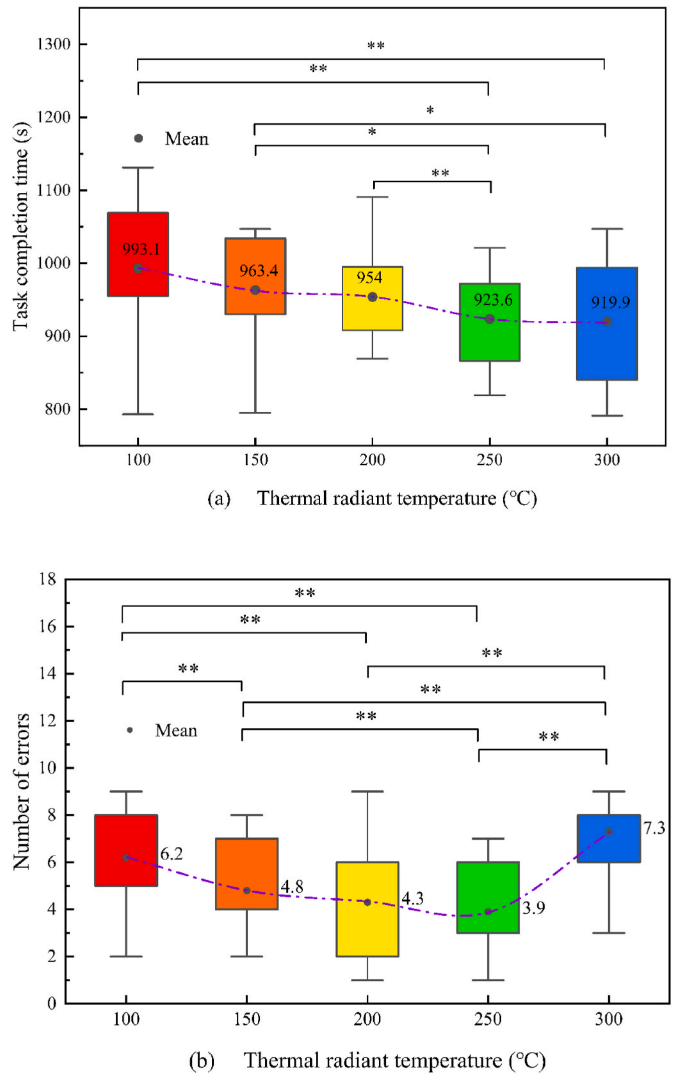

Fig. 7. Cognitive task performance: (a) task completion time; (b) number of errors (* shows significance difference ($P < 0.05$); ** shows significance difference ($P < 0.01$)).

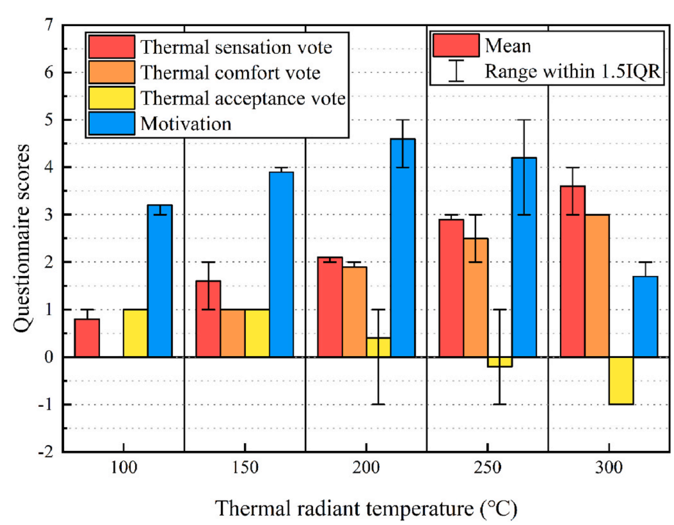

Fig. 8. Subjective questionnaire scores.

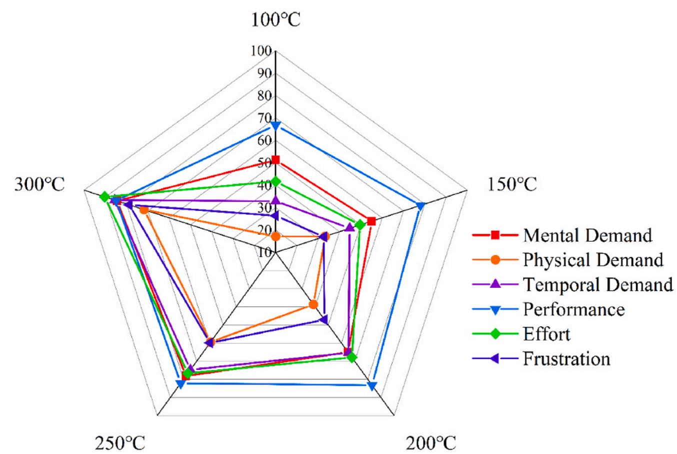

Fig. 9. NASA-TLX scores under different thermal radiation temperatures.

Table 5
The effect size and observed power of NASA-TLX.

	$P_{sphericity}$	F	P	η^2	Observed power
Mental Demand	0.124	167.442	<0.001	0.949	1
Physical Demand	0.065	395.735	<0.001	0.978	1
Temporal Demand	0.478	378.748	<0.001	0.977	1
Performance	0.298	20.957	<0.001	0.7	1
Effort	0.166	225.988	<0.001	0.962	1
Frustration	0.152	289.422	<0.001	0.970	1

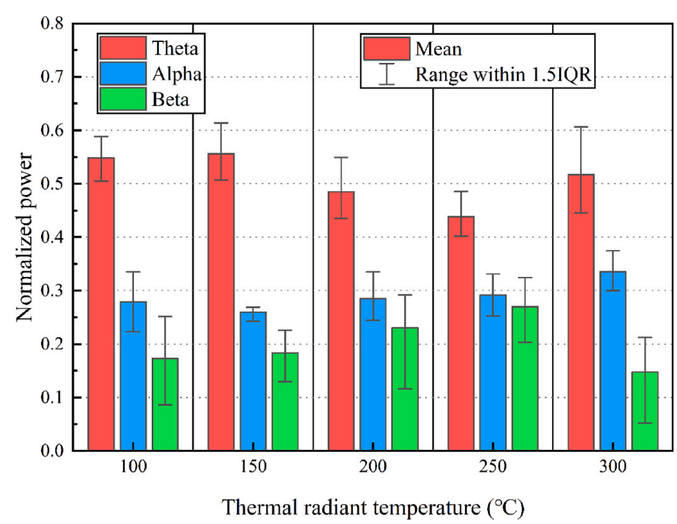

Fig. 10. The trend of the grand average of frequency band power (normalized power).

when the participants completed the cognitive test to assess their mental workload statuses by EEG measurement. It was observed that there was an apparent increase in arousal when the thermal radiant temperature changed from 100 °C to 250 °C. Meanwhile, the subjects mobilized a lot of attention to complete the test. However, this parameter drops again at 300 °C. Despite individual differences, it was observed that thermal radiant could lead to an uptrend in vigilance (100 °C–250 °C). The specific content is shown in Fig. 11. The detailed one way ANOVA and Bonferroni post hoc multiple comparisons results was in Appendix A.

3.4.3. Frontal EEG asymmetry

The forehead is an important area of the brain for cognition, emotion, reasoning, problem-solving, and other functions. The current

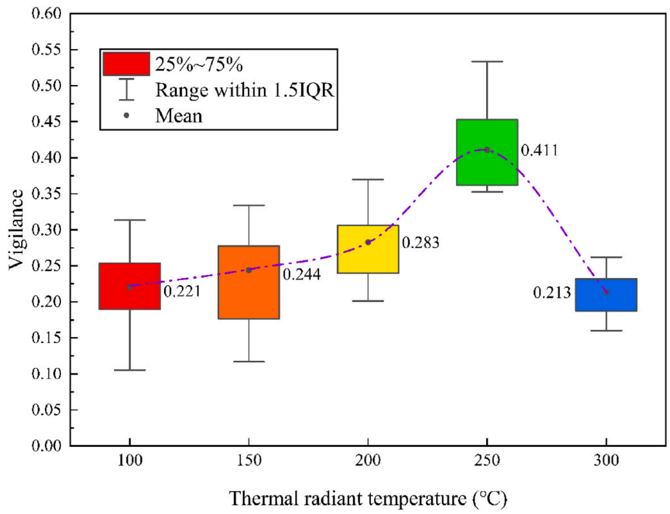

Fig. 11. The vigilance at various temperature levels.

state of brain emotional activity is quantified by calculating the asymmetry of the EEG of the forehead. It can be seen from Fig. 12 that the asymmetry of the forehead ($P_{sphericity} = 0.346 > 0.05$, $F = 13.562$, $P = 0.002$, $\eta^2 = 0.601$, Observed power = 0.964) raises with the radiation temperature reaching the peak at 200 °C and 250 °C, but decreasing again at 300 °C. Meanwhile, the excessive temperature is beyond the human body's adjustment range and affects the status of the brain. The frontal EEG asymmetry changed significantly ($P < 0.05$). The detailed one way ANOVA and Bonferroni post hoc multiple comparisons results was in Appendix A.

Previous neuroscientific studies suggest that assignments requiring continuous attention activate various brain regions. Meanwhile, the topographical distributions and developments of related frequency band powers (i.e., theta, alpha, and beta) were demonstrated [53]. It is used to describe the activity intensity, state, and vigilance of the cerebral cortex, and the average power spectral density of each rhythm is separated and normalized, in which red indicates a higher degree of activation. Due to paper length limitations, taking subject 6 as an illustration (The results in other subjects are similar to this example), the average distribution and development of theta, alpha, and beta power in five thermal radiant temperatures are presented in the following topology as is shown in Fig. 13. The amplitude of theta activity in the occipital lobe is the smallest at 250 °C, and the amplitude of the alpha activity in the parietal

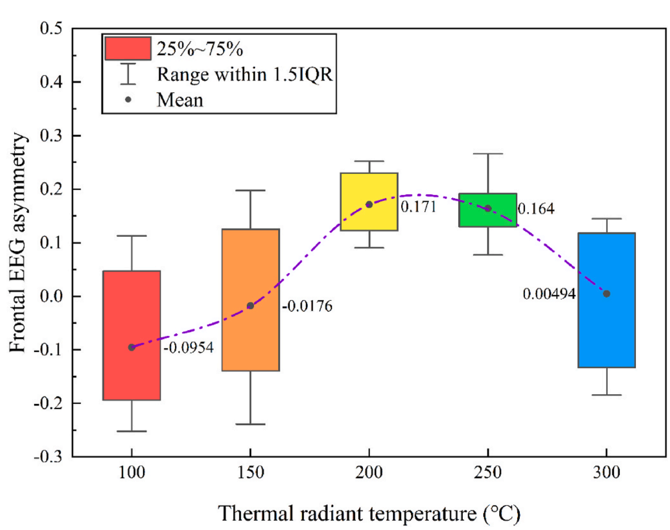

Fig. 12. Frontal EEG asymmetry at various temperature levels.

lobe of the brain is the smallest. Beta activity changes greatly in the forehead area at 250 °C, the average power increases in the left cluster of the forehead, the left frontal lobe is most activated, the left frontal lobe (AF3, F7, F3) is related to positive emotions, and the beta activity accounts for more in the left frontal lobe, the subjects were more positive at this time. This asymmetry was the significant difference among various thermal radiant temperatures in the EEG spectral measures. To summarize, PSD intensity was effectively utilized to distinguish between a vigilant state and a relaxed state, and frontal regions were more susceptible to vigilant tasks.

3.5. Correlation analysis

The relationships between the thermal radiant environment and other parameters such as cognitive abilities were investigated utilizing Pearson's correlation coefficients. Table 6 shows the correlation analysis results of thermal radiation temperature with different parameters. It was found through the analysis that there are significant negative relationships between the thermal radiant temperature on the one hand and the task completion time, TAV, and motivation score on the other hand. In contrast, there are significant positive relationships between the thermal radiant temperature on the one hand and TSV, TCV, mental demand, physical demand, temporal demand, performance, effort, frustration, and frontal EEG asymmetry on the other hand. However, the results showed no significant correlation between the number of errors, vigilance, and thermal radiant temperature. In other words, although the hyperthermal radiant environment may cause an increase in vigilance, the negative effect of high temperature is not counteracted by motivation or effort. Therefore, to describe the quantitative relationship among the number of errors, vigilance, and thermal radiant temperature, The results of the fit performed using polynomials for both variables are shown in Fig. 14. The polynomial fit lines indicate that most participants reached their peak point of alertness at approximately 250 °C.

4. Discussions

4.1. Effects of the local strong thermal radiation on performance

This study investigated the influences of the local strong thermal radiant upon the induction of mental statuses utilizing the neurophysiological method (EEG). The short testing period (60 min) and being monitored with participants to complete the simulation tasks during the experimental protocol contributed to these performance findings. The index of vigilance and FEA, which represent both the whole brain and the frontal cortex, show a significant difference. Despite individual variations, the cognitive task under hyperthermal radiant temperature (100 °C–250 °C) can lead to vigilance and arousal, as indicated in Figs. 11, Fig.12, and Fig. 13.

Subjects obtained some improvement in cognitive abilities when thermal radiant temperature varies from 100 °C to 250 °C. However, the augmented blood flow accompanying increased skin and forehead temperatures presents extra challenges to the heart and brain [18,56]. Meanwhile, the human body's thermal regulation system could no longer eliminate the influence of thermal load, and cognitive levels, tolerance, and physiological functions began to decline gradually. Hyperthermal radiant increased the subjects' TSV, TCV, motivation (100 °C–250 °C), and willingness to escape from the current environment.

Due to the extensive cognitive demand within constrained timeframes, subjects were forced to overdraw their brain power so far in advance that the completion speed increased from 100 °C–300 °C. However, when the temperature exceeds 250 °C, the thermal radiation will further penetrate the body surface and exert thermal stress on the brain nervous system which causes symptoms such as dizziness and thermal discomfort, an increase in the number of errors, operational

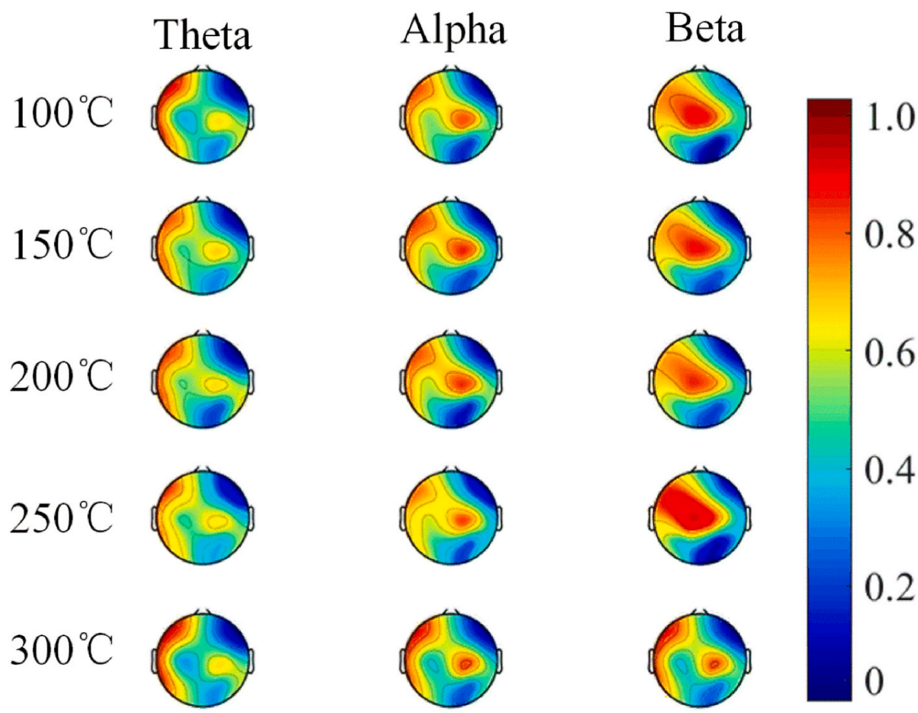

Fig. 13. Topographical distributions and developments of theta, alpha, and beta normalized power on average at various temperatures (Subject 6).

Table 6
Correlation analysis of thermal radiation temperature with different parameters.

Parameters	Correlation coefficient	*P*-value
Task completion time	−0.32	0.02
Number of errors	0.07	0.61
TSV	0.92	<0.001
TCV	0.95	<0.001
TAV	−0.76	<0.001
Motivation	−0.33	0.02
Mental Demand	0.95	<0.001
Physical Demand	0.97	<0.001
Temporal Demand	0.97	<0.001
Performance	0.72	<0.001
Effort	0.97	<0.001
Frustration	0.97	<0.001
Vigilance	0.24	0.1
FEA	0.36	0.01

mistakes, resulting in safety hazards. There is a subjective and objective mismatch between the increase of mental load and the improvement of intelligence level (shorter completion time and fewer errors) in the subjective questionnaire, so the cognitive status cannot be evaluated only by the subjective questionnaire. In other words, the increase in brain load and the decrease in efficacy felt by the subjects are not obvious in the level of intelligence. Wang et al. [58] noted that humans are not adept at recognizing when their vigilance is diminishing, and they may ignore or fail to be aware of the influences of the environment on their performance. Under high-temperature radiation, the subjects can obtain better results in a short time, but they are more prone to errors. Tian et al. [59] indicated that cognitive abilities can be improved in environments with extremely high temperatures and low indoor humidity. In addition, due to the pre-experimental enough training, these cognitive tasks become simple for the subjects. Zhang et al. [60] noted that the influence of temperature on cognitive performance depends on the complexity of the task. Simple tasks that require less attention are less likely to be affected by high temperature than complex tasks that require more attention. This is similar to the degree to of proficiency workers have for their jobs.

Interestingly, the thermal radiant temperature improved the alertness and excitement of the brain, enabling the subjects to complete tasks quickly. Under the influence of high temperature, beta activity and alpha activity are activated. Yao et al. [23] noted that the beta activity significantly increases when participants feel thermally uncomfortable, while the theta and delta activity decreases. Shan et al. [22] noted that the beta activities is associated with active thinking. In other words,

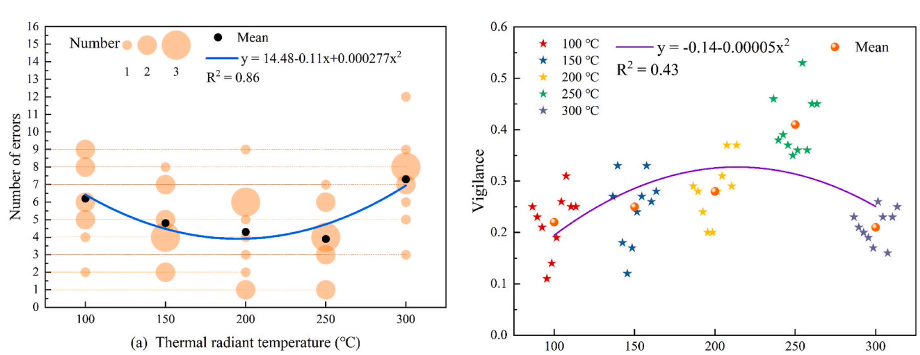

Fig. 14. Relationships between thermal radiant temperature and (a) number of errors; (b) vigilance.

when the subjects need to invest a lot of brain power to maintain high attention and vigilance, the brain activities will change to fast low amplitude beta activity, which causes the EEG nonlinear indicators (vigilance, forehead EEG asymmetry) to show an inverted "U" shape. Different regions of brain have different level of sensitivity to radiation, with prefrontal left areas shown to be more sensitive to heat and cognitive improvement [22].

In addition, there is a critical temperature threshold for cognitive abilities. More concretely, as heat ($T_T \leq 250$ °C, $T_W \leq 32$ °C, $T_A \leq 35.5$ °C, $F_{TR} \leq 750$ W/m^2) thresholds were reached, the greater the cognitive activities. However, beyond this threshold, cognitive performance begins to decline. To in-depth discuss the conclusions and practical applications of this study, as well as verify correctness, some guidelines and literature should be listed and compared with them. The details are shown in Table 7.

In GB 50019-2015 [11], the F_{TR} recommended range is 700W/m^2, which is close to our conclusion of 750 W/m^2. This indicates that when the thermal radiation flux density exceeds 700 W/m^2, people's cognitive abilities are reduced, which may lead to heat stress and safety accidents. When the ambient temperature is 23 °C, the subjects reached thermal comfort. Lorsch et al. [61] noted that when the ambient temperature exceeds the range (32–35 °C), the performance of mental tasks decreased. ISO 7243 [62] noted that When the WBGT over 28 °C, the performance of subjects declined. However, the subjects can maintain their performance to 32 °C. Some possible reasons for this will be explained in Section 4.2. Wing et al. [63] noted that when the temperature between 32.2 °C and 35 °C, the subjects' cognitive states began to drop significantly. Zhao et al. [64] noted that the when the WBGT reached 35 °C, the heat tolerance time decreased significantly. In summary, these findings can inform the design of thermal environment of buildings.

4.2. Effects of the motivation and effort on performance

In this study, a short-term cognitive test was performed at different thermal radiant temperatures. The result revealed that most people could achieve high performance, cognitive ability, and vigilance for a short time under hyperthermal radiant temperature conditions when they were deliberately investing a great number of mental efforts into task completion to compensate and offset the influences and effects caused by hyperthermal radiant temperature conditions. The motivation and the effort may be the possible reasons for the arousal effect. There are some theoretical mechanisms to interpret this phenomenon.

1. The maximum adaptability model suggests cognitive improvement originated from adaptive responses to heat strain, such as enhanced concentration. However, as hyperthermal radiant temperature increases, heat strain-induced exhaustion of mental and attentional resources leads to cognitive performance decrement [65].
2. During the short period, participants can sustain their behaviors at a relatively high level even if the environmental state is uncomfortable and unfavorable. It was discovered that participants' motivation took precedence to influence their performance in adverse situations (heat strain). The increased mental workload could be construed as participants attempting to put more effort into the assignment to neutralize the adverse influence of hyperthermal radiant temperature on their performance [43].
3. The processing efficiency theory suggests despite being told that this experiment was anonymous, subjects remained conscious of their cognitive abilities and performance, and monitored its development sufficiently to identify problems in processing or efficiency. They could also introduce remedial and corrective strategies and deploy compensatory resources to deal with the identified problems. Therefore, the cognitive system is flexibly guided by a self-regulatory mechanism that detects and evaluates present results and actively deploys resources and methods to enhance performance [66].

Table 7
Comparison of the finding of this study with the relevant literature and guidelines.

Guidelines or literature	items	Recommended range	Our conclusions
GB 50019-2015 [11]	F_{TR}	<700W/m^2	≤750 W/m^2
GB 50019-2015	Thermal comfort	18–24 °C	23 °C
Lorsch [61]	T_A	32–35 °C	35.5 °C
ISO 7243 [62]	T_W	<28 °C	32 °C
Wing [63]	T_A	32.2–35 °C	35.5 °C
Zhao [64]	T_W	35 °C	32 °C

4.3. Some physiological explanations

The human body can maintain a good thermal balance in a thermally neutral environment. However, corresponding stress responses are performed when the external environment reaches an unfavorable situation (hyperthermal), and these reactions contribute to evading dangerous conditions. The sympathetic nervous system is activated, stimulating the adrenal medullary cells to release the hormones epinephrine and norepinephrine, and the combined action of these hormones and the sympathetic nervous system results in a "fight" or "flight" response that includes increased heart rate, vasodilation. Blood flow increases, glucose is released into the bloodstream from the hepatica and skeletal muscle, resulting in increased blood glucose levels, the brain, skeletal muscle vasodilation, resulting in increased blood supply to the brain and heart, and increased blood glucose levels because of adrenaline, which provides energy to the muscles, heart, and brain [67].

The "fight-or-flight" response theory suggests cognitive improvement resulting from the release of hormones. When under adverse circumstances, the sympathetic nervous system is activated by a sudden release of hormones that trigger catecholamines (including adrenal glands and norepinephrine), which increases arousal and ultimately completes tasks quickly [68].

5. Limitations and future work

Although this investigation was carried out in relatively controlled circumstances, some potential limitations were encountered. In the climate chamber, the local strong thermal radiant temperature is exceedingly lower than the working temperature of the actual heat treatment workshop. The main reason is that the higher temperature may cause physical damage to the subjects, or the completion rate of the experiment is insufficient. Furthermore, the participants were predominantly young and all graduate students, which differed greatly from the level of education, proficiency, thermal acclimatization, etc. of the operators. However, although the subjects all youngsters, the results of this study can also provide some basis for changes in the cognitive abilities of young employees in industrial workshops. At last, despite the sample size being sufficient to investigate EEG activity, to be able to promote the consequences to the general population, different distances and chamber areas, different exposure durations, a control group without the influence of radiant, larger sample, more hyperthermal radiant temperature levels, female subjects, and workers in real heat treatment workshop on-site should include in future studies. Following this method, targeted and individualized vigilance management strategies can be established to deliver practical benefits in the management of heat treatment industries' safety.

6. Conclusions

The present study demonstrated LSTR environment can affect brain cortex activity, and EEG signals can be identified as a biological indicator of environmental changes. Below are the detailed practical implications of the study results.

(1) Cognitive performance, questionnaire, and EEG features that show neurophysiological responses to LSTR condition changes were significant representatives of vigilance and cognitive abilities. That is, a short-term hyperthermal radiant temperature environment can improve people's alertness and excitement. Hot ($T_T \leq 250$ °C; $T_W \leq 32$ °C; $T_A \leq 35.5$ °C, $F_{TR} \leq 750$ W/m^2) threshold was optimum for vigilance and performance. When the radiation temperature $T_T \leq 250$ °C, the subjects work more efficiently and cognitively perform better under high-temperature radiation. When $T_T > 250$ °C, the number of errors increases. As the radiant temperature increases, thermal sensation, thermal comfort increase, and thermal acceptability decrease.
(2) The influence of high-temperature thermal radiation on EEG characteristics, the components of β activity and α activity increase, the level of alertness and forehead asymmetry all increase, and when $T_T > 250$ °C, these characteristic indicators decrease again, showing an inverted "U" shape. Different regions of brain have different level of sensitivity to radiation, with prefrontal left areas shown to be more sensitive to heat and cognitive improvement.
(3) The "flight-or-fight", motivation, and processing efficiency theory can provide a theoretical basis for the cognitive changes in LSTR. Short-term (60min) high temperature ($T_T \leq 250$ °C) heat radiation will improve motivation and cognitive performance, which provides a certain basis for productivity improvement and safety management of heat treatment industries and indoor ultra-high temperature radiant work.

CRediT authorship contribution statement

Haobo Niu: Writing – original draft, Data curation. **Yingni Zhai:** Formal analysis, Data curation. **Yanqiu Huang:** Funding acquisition. **Xianglin Wang:** Data curation. **Xinta Wang:** Data curation.

Declaration of competing interest

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.

Data availability

The data that has been used is confidential.

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Appendix

A. Table Multiple comparisons (Bonferroni correction) of different parametric indexes under different thermal radiant panel's temperature. (Note: 100 °C, 150 °C, 200 °C, 250 °C, 300 °C is represented using T_1, T_2, T_3, T_4, T_5, respectively).

	T_1				T_2			T_3		T_4
	T_2	T_3	T_4	T_5	T_3	T_4	T_5	T_4	T_5	T_5
T_W	**	**	**	**	**	**	**	**	**	–
T_A	**	**	**	**	**	**	**	**	**	*
TSV	*	**	**	**	–	*	**	**	**	–
TCV	–	–	**	**	–	*	*	**	–	–
TAV	–	–	–	–	–	–	–	–	*	–
Motivation	–	**	–	**	*	–	**	–	**	**
Mental Demand	–	**	**	**	**	**	**	**	**	*
Physical Demand	**	**	**	**	*	**	**	**	**	**
Temporal Demand	**	**	**	**	**	**	**	**	**	**
Performance	–	**	**	**	–	–	*	–	–	–
Effort	*	**	**	**	**	**	**	**	**	**
Frustration	–	**	**	**	**	**	**	**	**	**
Vigilance	–	**	**	–	–	**	–	**	**	**
FEA	–	**	**	–	*	*	–	–	*	**

Note: "*"shows significance difference ($P < 0.05$); "**" shows significance difference ($P < 0.01$); "-" shows no significance difference($P > 0.05$).

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