Building and Environment 186 (2020) 107372

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

High temperature impairs cognitive performance during a moderate intensity activity

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A R T I C L E I N F O

Keywords:
High temperature
Moderate-intensity activity
Cognitive performance
Thermal comfort

A B S T R A C T

High temperatures are one of the main causes of work safety accidents associated with cognitive impairment. However, the effects of elevated ambient temperature on cognitive performance during moderate-intensity activities are unclear. In this study, subjects (N = 32) were exposed to four different air temperatures, i.e., 26, 30, 33, and 37 °C, and a relative humidity of 70% in a climate chamber. During the experiment, the subjects were required to complete neurobehavioral cognitive tests while walking on a treadmill with an estimated metabolic rate of 165 W/m^2. During the 90-min experiment, the tympanic temperature, weight loss, heart rate, and percentage of adjacent inter-beat cardiac intervals differing by > 50 ms (pNN50) were measured. Subjective responses were collected using questionnaires.The accuracy of subjects' responses to the semantic interference and visual perception tests were significantly decreased at 37 °C after 45 min of exercise. Additionally, over the exposure period at 37 °C, the accuracy of various cognitive tests also decreased, while the speed increased. The changes in the cognitive test results at 37 °C were associated with the elevation of the tympanic temperature, heart rate, dehydration rate, and decline of the pNN50. Similarly, the elevated thermal discomfort and intensity of neurobehavioral symptoms were related to these changes.In conclusion, exposure to a temperature of 37 °C for 45 min has a negative impact on the accuracy of personnel with moderate-activity intensity. Therefore, 45 min is recommended as a safe time for continuous work with moderate intensity at 37 °C.

1. Introduction

With the frequent occurrence of high-temperature events, workers are facing increasing risk. Not only do such events result in lower operating efficiency, but they also result in higher accident rates, as indicated by big data surveys conducted in several regions. For example, with an increase in the daily maximum temperature of 1 °C from 2000 to 2011, the traffic accident risk due to the decreased efficiency of drivers has risen by 1.1% in Catalonia, Spain [1]. In Adelaide, Australia, the number of daily work-related injuries increased by 0.2% with an increase in the daily maximum temperature of 1 °C from 2001 to 2010 [2]. Additionally, during the summer of 2014, the working time of rebar workers in two construction projects decreased by 0.57% as the outdoor Wet Bulb Globe Temperature (WBGT) temperature increased by 1 °C in Beijing, China [3]. Studies based on global data predicted that the working capacity during the hottest months will decrease by 20% in 2050 and by 60% in 2200 due to climate warming [4]. Decreases in cognitive performance are an underlying cause of these risks, but more direct evidence is required to support this theory.

Previous studies investigated the effects of high temperature on cognitive performance after exercise. A detailed literature review is provided in the supplementary material (Appendix A). These experiments were conducted with moderate-intensity exercise or higher, and the results were as follows: (1) extreme temperatures of 39 °C and above impair the accuracy of responses to post-exercise cognitive tests. First, the accuracy of the completion of cognitive tests post-exercise at high temperatures was lower than before exercise [5–7]. These cognitive tests assess the subjects' substitution, concentration, perceptual-motor coordination, thinking, and recognition abilities. Second, the accuracy of all cognitive tests post-exercise at high temperature was lower than that at normal temperature [7–9]. These cognitive tests assessed the attention, reaction, working memory, and visual memory of the subjects. (2) At extreme temperatures of 39 °C and above, subjects completed cognitive tests reflecting their memory, reflexes, and thinking abilities more quickly post-exercise (8), but completed cognitive tests reflecting their attention less quickly [6,7]. (3) For the professional personnel who received heat acclimation training, the high temperature range of 39–45 °C did not significantly impact the accuracy and speed of the

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https://doi.org/10.1016/j.buildenv.2020.107372
Received 26 July 2020; Received in revised form 6 October 2020; Accepted 11 October 2020
Available online 13 October 2020
0360-1323/

completion of cognitive tests post-exercise.

The effects of general temperatures of 33–35 °C on post-exercise cognitive performance have been inconsistent in different studies. Some studies found a decrement in the accuracy of cognitive tests post-exercise [10], while others found an increment in the speed post-exercise [10,11], and others reported no effect [12–14]. Therefore, further investigations are required to clarify these contradictions.

Additionally, previous studies are limited by the following two points: (1) Experimental data collected under high-temperature conditions below 39 °C are very limited, particularly at temperatures between 35 and 39 °C, which is a common summer high-temperature range in hot and humid regions, and (2) most experiments had subjects' complete cognitive tests after exercise, which may not reliably reflect cognitive performance during exercise. These developments have considerable potential and should be focused on in follow-up studies.

This study explores the impact of elevated temperature under moderate-intensity exercise on cognitive performance in a climate chamber experiment at 33–37 °C. Cognitive performance was assessed by conducting cognitive tests that reflect semantic interference, visual perception and the spatial positioning ability, responding to visual signals, thinking, and arousal level [15–17]. This study also explored the main causes of the influence, combining the measured physiological parameters and subjective responses. This study is more appropriate for actual operative situations. First, most labor activities are moderate in intensity, such as walking at a moderate pace, site work, and farm work [18]. Second, in contrast to the experimental design of other studies, the subjects of this study were required to complete all cognitive tests during exercise, rather than after exercise. The results are expected to provide a theoretical basis for determining the safety limit temperature of workers with moderate-intensity labor from the perspective of cognitive performance. Therefore, it was necessary to conduct this work.

2. Methods

2.1. Approach

The subjects were exposed to four air temperatures (26, 30, 33, and 37 °C) with a relative humidity of 70%. The order of exposure followed a 4 × 4 Latin square design (Appendix B, Table B1) to reduce potential effects that could result from the order of exposure to different conditions. Thirty-two subjects were recruited and randomly divided into four groups of eight. Each subject experienced all experimental conditions following a within-subjects design. The subjects were required to walk on a treadmill at a constant speed of 4 km/h without slope for 85 min. When walking on the treadmill, the subjects were required to complete cognitive tests and subjective questionnaires at the specified time while their physiological parameters were measured.

2.2. Facilities

The experiment was conducted in a 4 × 3.3 × 2.8-m^3 climate chamber located at the Railway Campus of the Central South University of China. The walls of the climate chamber were composed of stainless steel, with adequate sealing and thermal insulation and no odors. The layout of the chamber is shown in Fig. 1a. All furniture, equipment, and instruments were cleaned repeatedly, and all of the furniture, the treadmill, computers, and equipment had no odor distribution. A top-view of the climate chamber is shown in Fig. 1b. During the experiment, there was only one researcher and one subject in the climatic chamber.

During the experiment, fresh air was provided from outdoors, with an air volume of 1000 m^3/h. To maintain the indoor air quality, the indoor air distribution was in the form of up-supply down-return, with a ventilation rate of >10 h^{-1}.

Table 1
Physical measurements in the climate chamber (mean ± SD) at different experimental conditions.

Condition	26 °C	30 °C	33 °C	37 °C
Air temperature (°C)	26.2 ± 0.2	30.1 ± 0.2	33.2 ± 0.2	37.0 ± 0.2
Relative humidity (%)	70 ± 1	70 ± 2	70 ± 1	69 ± 2
Black-global temperature (°C)	26.8 ± 0.2	30.8 ± 0.2	33.8 ± 0.2	37.6 ± 0.1
Illumination (lum/ft^2)	14.9 ± 1.5	15.7 ± 1.1	15.7 ± 1.2	15.6 ± 1.5
Air velocity (m/s)	0.03 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
CO_2 concentration (ppm)	458 ± 22	467 ± 20	489 ± 28	501 ± 37

2.3. Experimental conditions

There are 4 levels of temperature conditions in the experiment: 26 °C, 30 °C, 33 °C, and 37 °C 26 °C is the minimum setting for air conditioning that is recommended for public buildings during the summer by the Chinese government [19]. The temperature of 30 °C was chosen because it may induce heat stress: It is expected that the hypothalamus will begin regulating the body temperature at this temperature level [20]. The temperature of 33 °C was chosen because it is used in China as a temperature level above which employers must pay a "high-temperature subsidy" to their employees [21]. The temperature of 37 °C is chosen because it is close to the normal human body core temperature. In China, an outdoor temperature of 37 °C is also the action level at which a high temperature "orange warning" alert is issued, meaning that people are warned to avoid outdoor activities and pay attention to preventing heatstroke when the maximum temperature rises to above 37 °C within 24 h. The relative humidity of 70% was selected because it is often recommended as the upper limit for thermal comfort in hot and humid environments [22].

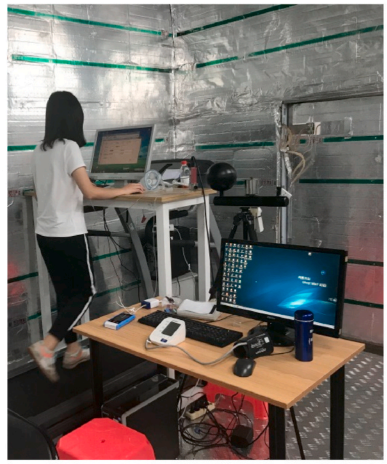
Before the experiment, the air velocity was measured at six points in the climatic chamber (see Fig. 1b points 1–6). The average air velocity measured in the occupied zone was <0.1 m/s (Appendix C, Figure C1). The measuring points were located 1.2 m from the walls at a height of 1.0 m.

The illumination level remained constant. No other sources of heat, pollution, or noise were present either inside or outside the chamber.

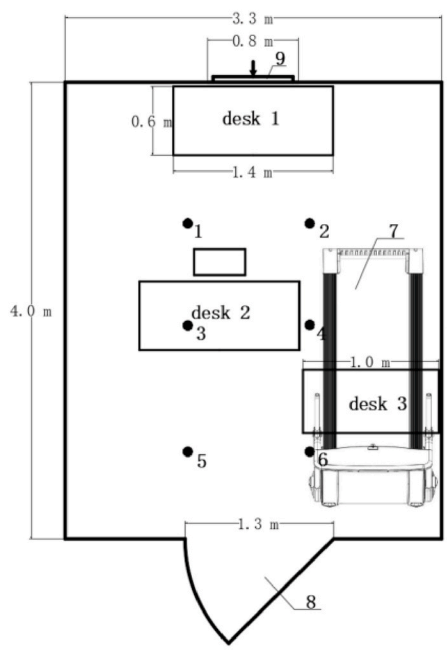
During the experiment, the subjects were required to walk at a speed of 4 km/h on a no-slope treadmill (SH-5110A, SHUA, China). Based on the exhaled gas flow rate and exhaled CO_2 (O_2) concentration measured during the experiment, the estimated mean metabolic rate during the experiment was 165 W/m^2, which was within the medium metabolic rate range stipulated by ISO8996 (130–200W/m^2) [18]. The intensity of the exercise in this experiment was medium, and the metabolic rate was estimated based on the exhaled gas flow rate and exhaled CO_2 (O_2) concentration [18], as shown in the supplemental material (Appendix D).

2.4. Subjects

Thirty-two subjects (16 female and 16 male) were recruited through advertisements distributed within the university campus and on the university website, who were healthy and had long-term exercise experience. Before the experiment, a physical fitness test was conducted for the registered subjects, which involved walking on the treadmill at 3 km/h for 90 min. If they successfully completed the test without any discomfort, they were allowed to participate in the experiment. The subjects were divided into four groups of four males and four females, who were undergraduate or graduate students (age 23.0 ± 1.5 years, height 166.8 ± 8.3 cm, and weight 56.7 ± 11.6 kg). All subjects reported no history of the disease (such as hypertension or cardiovascular disease), were in good health, non-smoking, were not chronically ill, did not take any medication during the experimental periods, had no history of cardiovascular disease, and were not color blind. All of the subjects



(a) The snapshot of the chamber during experiments.



(b) The layout of the experiment chamber. (1-6. air velocity measuring points; 7. a treadmill; 8. door; 9. air inlet and outlet)

Fig. 1. Schematic diagram of the climate chamber.

had lived in Changsha, China, for over one year and experienced high-temperature weather. The subjects were reminded to avoid caffeine, alcohol, and strenuous activities both before and during the experiment, and to sleep well at night. The experiments were arranged to avoid influences of menstruation.

All subjects had good English skills and could accurately understand the contents of the subjective questionnaire and cognitive tests during the experiment. None of the subjects had taken or known of any cognitive tests before the experiment. To avoid the influence of subjective psychological factors on the experimental results, the subjects were not informed of any of the experimental conditions during the experiment.

The subjects were asked to wear typical summer clothing during the experiment, which consisted of a short-sleeved T-shirt, thin trousers, sports shoes, socks, and underwear. The clothing thermal resistance is approximately 0.39 clo [23].

The study conformed to the standards set by the Declaration of Helsinki and was approved by the Human Ethics Committee in the First Affiliated Hospital of Hunan University of Chinese Medicine (AF/SC-07/02.0). The subjects were informed in detail to understand the experimental procedures and precautions. Prior to the experiment, subjects needed to provide written informed consent, and were paid a certain amount of money while completing the experiment.

2.5. *Measurements*

2.5.1. *Physical measurements*

The air temperature, relative humidity, illumination, and CO_2 concentration in the chamber were continuously measured by HOBO data loggers (HOBO data logger, Onset Computer Corp., Bourne, MA, USA) at the center of the chamber. A portable WBGT heat index instrument (JTR10, JANTYTECH, Beijing, China) was used to measure the indoor black ball temperature, which was recorded manually by the experimenter every 5 min.

2.5.2. Physiological measurements

Multiple physiological parameters were measured during the experiment (see Fig. 2), including the subjects' tympanic temperature, heart rate and its variability, and exhalation flow and CO_2 and O_2 concentrations. The tympanic membrane temperature and heart rate, and its variability, can reflect heat stress [5]. The exhalation flow and CO_2 and O_2 concentrations were used to estimate the metabolic rate during the experiment.

The tympanic temperature was measured using a ThermoScan thermometer (TH839S, OMRON, Tokyo, Japan). The tympanic temperature is one of the core temperature indices, and changes in its value can reflect the changes in brain temperature [24].

The subjects' heart rate was monitored throughout the experiment using a commercial heart rate monitor (Dual Belt, Suunto, Vantaa, Finland) consisting of a chest strap with electrodes. The heart rate and inter-beat interval (IBI) were recorded every second. Before the beginning of the experiment, the heart rate monitor was tied to the chest close to the heart, with the electrodes facing forward.

In accordance with the IBI data, the time domain index of the heart rate variability (pNN50) was calculated, which represents the percentage of adjacent heart and inter beat intervals that differed by > 50 ms [25]. pNN50 is one of the indicators that can reflect the activity of human sympathetic and parasympathetic nerves [26], as well as the heat stress of the human body [27].

The subjects' body weight was measured before and after each exposure using a high-precision scale (150K20D, KERNDE, Groβmaischeid, Germany). The weight of water consumed by the subjects during each experiment was subtracted. The body weight loss (BWL) was calculated as follows [28]:

$$BWL = m_1 + m_{w_1} - m_2 - m_{w_2} \tag{1}$$

where m_1 and m_2 represent the body weights (kg) of the subjects before and after the experiment under the same conditions. m_{w1} and m_{w2} represent the quantity of bottled purified water (including bottle weight) before the experiment under the same conditions and the quantity remaining after the experiment, respectively.

The dehydration rate can be calculated from the subject's weight and weight loss, as follows [18]:

$$Dehydration\ rate = BWL/m_1 \tag{2}$$

2.5.3. Subjective measurements

Subjects' thermal sensation, alertness, and neurobehavioral symptoms during the experiment were voted by paper questionnaires. These questionnaires have been applied to relevant studies [29,45]. Questionnaires were used to obtain subjective responses. They included questions regarding thermal sensation, and acceptability of the thermal environment in the climate chamber (TC), Alertness (ALT) and the intensity of any acute health symptoms. All the questionnaires were presented in English.

The thermal sensation vote adopts the following 9-point continuous scale: very cold(-4)、cold(-3)、cool(-2)、slightly cool(-1)、neutral (0)、slightly warm(1)、warm(2)、hot(3)、very hot(4),which is the extension of ASHARE 7-point scale [23].Thermal comfort voting adopts the following 6-point fracture scale: very uncomfortable(-2)、uncomfortable(-1)、just uncomfortable(-0.01)/just comfortable (0.01)、comfortable (1)、very comfortable (2).Thermal acceptability voting adopts the fracture scale: clearly unacceptable(-1)、just unacceptable (-0.01)/just acceptable(0.01)、clearly acceptable(1).

The alertness is assessed on the following 9-point continuous scale: very sleepy(-4)、sleepy, some effort to stay awake(-3)、sleepy, no effort to stay awake (−2)、some signs of sleepiness(-1)、neither alert nor sleepy(0)、rather alert(1)、alert(2)、very alert(3)、 extremely alert (4).

The neurobehavioral related symptoms are part of the subjective questionnaire for acute health symptoms, including: headache[no(0) – severe(100)], concentration[easy(0) – hard(100)], thinking[clear(0) – difficult(100)], fatigue [rested (0) – tired (100)] and dizzy [not dizzy (0) – dizzy (100)].The voting values of all symptoms were evaluated on a continuous scale from 0 to 100. The larger the voting values were, the more severe the symptoms were.

2.5.4. Performance measurements

Neurobehavioral and Tsai-Partington tests were conducted during the experiment. Neurobehavioral tests have been used to evaluate the effects of indoor environmental quality on human performance in recent years [29,30,44], and the Stroop, redirection, addition and visual react tests were conducted here.

Stroop is a semantic interference and visual perception task [15]. A word indicating the name of random colors was presented on the computer screen, but the word itself was displayed in another color, such as the word "yellow" displayed in red. The subject was required to identify the content or color of the word according to the topic and select the appropriate option. The test included a total of 100 items, and the given time to complete the test was 180 s.

Redirection was employed to investigate the spatial positioning ability of the subject [15]. At the beginning of the test, an image of a hand-held black disc appeared on the screen. The image was randomly presented in four forms: upright, inverted, facing the subject, and with its back turned to the subject. The subjects were required to judge whether the black disc was placed on their left or right based on the

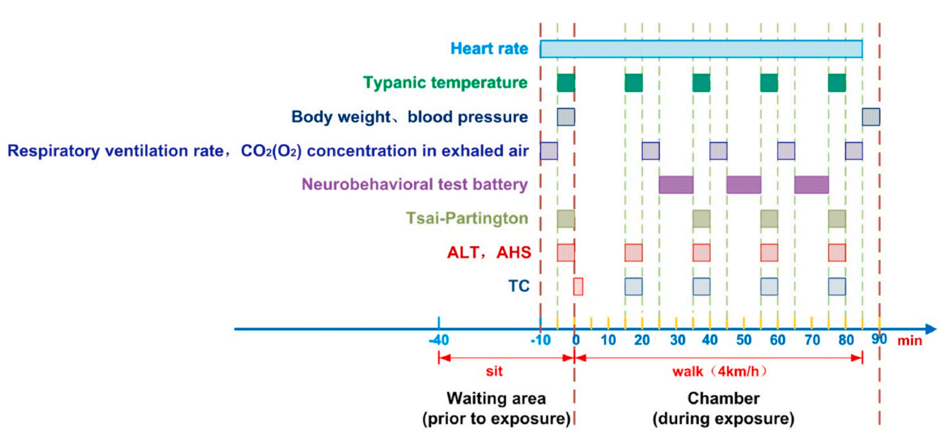


Fig. 2. Formal experimental schedule.

facial features of the image. The test included a total of 150 items, and the given time to finish the test was 180 s.

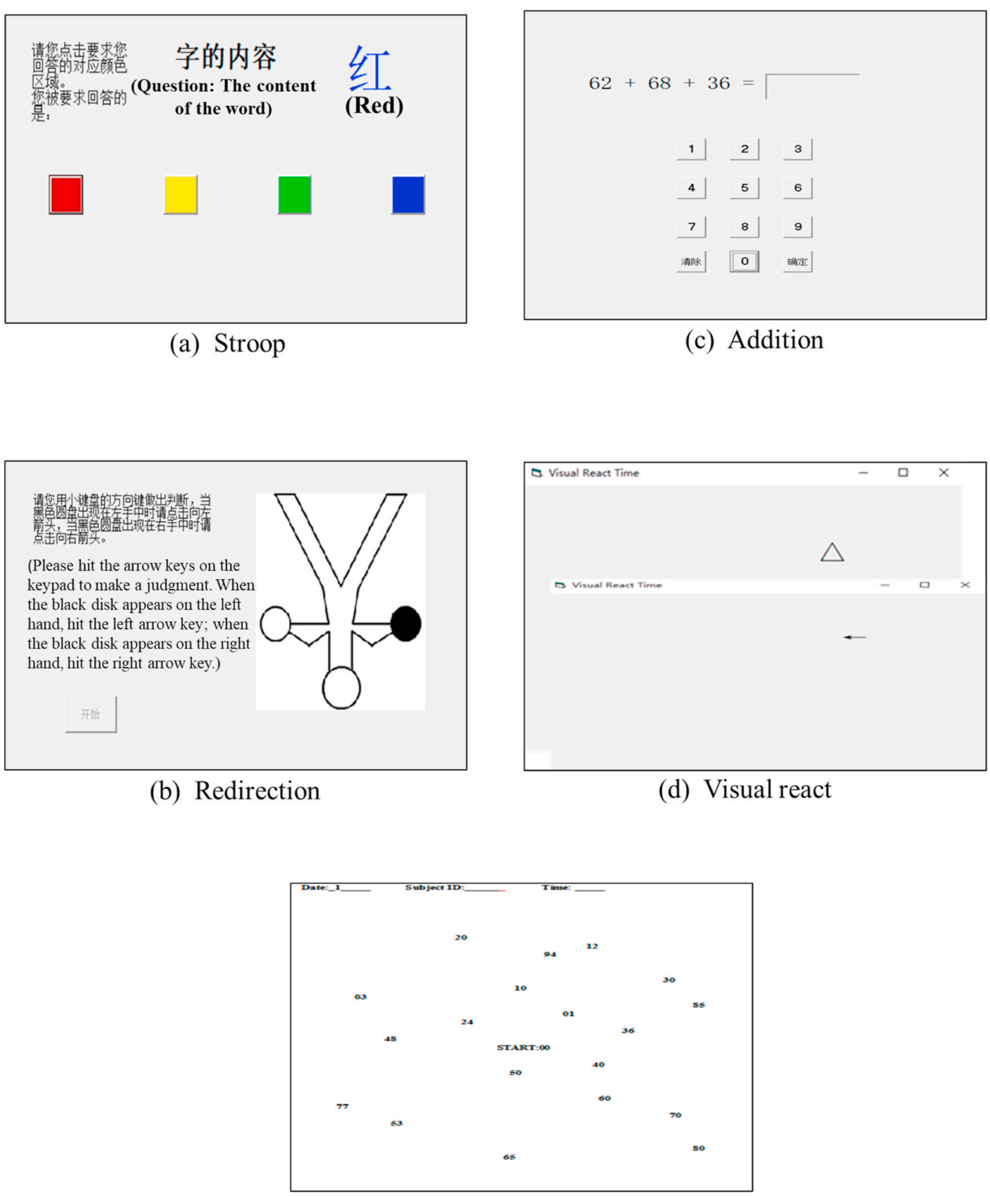
Addition is a digital mental arithmetic task applied to investigate an individual's thinking ability [16]. In these experiments, the subjects were required to obtain an answer by mental arithmetic, and then enter the result using the numeric keypad on the screen. The test included a total of 15 items, and the given time to finish the test was 180 s.

Visual react is employed to test an individual's ability to respond to visual signals [17]. The following stimuli were displayed randomly on the left or right side of the screen: "←", "→", and "Δ". The subjects were asked to press the left arrow key on the keyboard when the "←" stimulus appeared, and the right arrow key when the "→" stimulus appeared. If the "Δ" stimulus appeared on the left or right side of the screen, the subjects were required to press the corresponding left or right arrow key on the keyboard. The test included 100 items, and the time to finish the test was 60 s.

The Tsai-Partington test is generally applied to evaluate the arousal level [31]. In this test, 20 random numbers from 0 to 100 were randomly distributed on a piece of paper. The subjects were then required to connect the numbers in ascending order within 40 s. The test scores were based on the response speed and accuracy.

The cognitive test was conducted in the following order: Stroop, redirection, addition, visual react, and Tsai-Partington. The total time to complete the cognitive test was 15 min, and all subjects completed all cognitive tests within the given time. The neural behavior testing software interface and Tsai-Partington test were used in this study, as shown in Fig. 3.

(a) Instances of Stroop test. Stimuli were presented in Chinese. Their English translations are indicated in parentheses. The subjects were required to answer the question presented in Chinese. (b) Instances of redirection test. The subjects were required to judge the position of the black disc. The description of the test was presented in Chinese for the subjects. Its English translations is indicated in parentheses. (c) Instances of addition test. The subjects were required to input the answer in the box behind the equation. (d) Instances of visual react test. Stimuli were presented in graphs. (e) Instances of Tsai-Partington test. The subjects were required to connect the numbers in ascending order.



(a) Stroop
(c) Addition
(b) Redirection
(d) Visual react
(e)Tsai-partington

Fig. 3. The tests used to measure cognitive function.

2.6. Procedure

The experiment was conducted from September to October 2017. All subjects were exposed to the four designed environmental conditions, and the same experimental temperature sequence was used for all subjects within a group (Appendix B, Table B1). The eight subjects in each group were randomly divided into two groups of two males and two females. One group experienced the first temperature condition during the afternoon of the first day, while the other group experienced the same condition at the same time on the following day. Each group of subjects rested for one day before participating in the next experiment under different experimental conditions.

The subjects participated in the practice experiment for two consecutive days before the formal experiment. The practice experiments were conducted from 09:00 to 12:00 and 14:00 to 17:00 in a laboratory simulating an office environment on the first day, and in the climate chamber on the second day for the formal experiment. The temperatures were set at 26 °C on both days with independently controlled humidity. On the first day, four subjects and one researcher were present in the laboratory. With the guidance of the researcher, the subjects carefully read and completed the subjective questionnaire, repeated the neurobehavioral tests used in the formal experiment six times, and the Tsai-Partington test eight times. On the second day, the subjects were required to correctly wear the physiological measurement instruments, such as the heart rate monitor, with the guidance of the researcher and follow the formal experimental procedure on the treadmill twice. The neurobehavioral tests adopted in the formal experiment were repeated four times, and the Tsai-Partington test was conducted six times. The subjects rested for one day between completing the practice experiments and participating in the formal experiment.

The 90-min formal experiments were conducted during the afternoon of each day, which was divided into four periods: 12:30–14:00, 14:15–15:45, 16:00–17:30, and 17:45–19:15. One subject was assigned to participate in the experiment during each period, and each subject participated at the same time of the day. Prior to exposure, the subjects remained in the waiting room for approximately 40 min, where the temperature was maintained at 26 °C and the relative humidity was not controlled. Once the subjects arrived at the break room, they were required to complete a questionnaire with basic information, including their sleep condition, activity level, whether they drank stimulating drinks, such as coffee or wine, and whether they took drugs. After adapting to the ambient temperature, the subjects removed their clothes in the dressing room, measured their weight in their underwear, and then wore a heart rate monitor and experimental clothing. The researcher checked that the instruments had been fitted appropriately. Ten minutes before starting the experiment, the subjects measured their exhaled CO_2 and O_2 concentrations and airflow with the assistance of the researcher. After 5 min, the subjects completed the acute health symptom and alertness questionnaires, and completed the Tsai-Partington tests.

After 40 min of preparation, the subjects entered the climatic chamber and completed the TC questionnaire to immediately assess their initial perception of the climatic chamber environment. Upon completing the TC questionnaire, the researcher set the treadmill to 4 km/h with uniform acceleration within 5 s, and the subjects began to walk at a uniform speed. The experimenter measured the right-eardrum temperature of the subject after 15 min, and the subject completed the TC, ALT, and AHS questionnaires. After 5 min, the subjects measured their exhalation CO_2 and O_2 concentrations and exhalation flow with the assistance of the researcher. These operations were repeated every 20 min four times. The subject underwent neurobehavioral tests and the Tsai-Partington test every 20 min for three 15-min sessions from minute 25. After completing the experimental sessions, the subjects left the climate chamber and entered the dressing room to remove their experimental clothing, the heart rate monitor, and other wearable instruments. They then measured their weight in their underwear. The subjects were informed that they could leave the climate chamber at any time if they felt extremely uncomfortable or they could not continue the experiment; however, no subject did so. The subjects were rehydrated at a specified time after each exhalation flow measurement, and the formal experimental procedure is shown in Fig. 2. Here, we mainly analyzed the relationship between temperature, physiological parameters, and cognitive performance.

2.7. Statistical analysis

The general linear model repeated measures procedure was following to examine the effects of the different temperatures, times, and their interactions on the performances of the subjects in the cognitive tests, physiological parameters, and subjective responses. The exposure temperature, time, days, and subject data were used as independent variables. For the test scores that were significantly affected by temperature, the Bonferroni method was used for the post-hoc comparison of the differences in test scores during the same period between different temperatures. For the test scores that were significantly affected by time, the Bonferroni method was used for the post-hoc comparison of the differences in test scores at the same temperature between the different time periods.

All analyses were conducted SPSS v20.0 (SPSS Inc., Chicago, IL, USA), excluding the results of the page test, which were analyzed using Statext v2.7 (Statext LLC, Wayne, NJ, USA). The significance level was set at $P = 0.05$ (1-tail).

3. Results

3.1. Measured physical parameters

Table 1 lists the mean and standard deviation values of all physical parameters measured in the climate chamber under different exposure conditions. The measured air temperature and relative humidity only slightly differed from the intended levels: The deviation between the set and measured temperature values did not exceed 0.4 °C, and the relative humidity was within ±3%. The measured WBGT under each condition only slightly exceeded the ambient temperature. The illumination intensity in the climatic chamber did not change during the experiment. The measured air velocity at the measuring point (point 4 in Fig. 1b) near the subject was below 0.1 m/s, which did not cause a draught sensation. The CO_2 levels measured in the climate chamber increased slightly. but systematically. with the air temperature and remained within the range of 450–500 ppm.

3.2. Cognitive performance at elevated temperatures

The variations in the cognitive test scores with the number of repetitions in the practice and formal experiments were analyzed (Appendix E, Figure E1) at beginning of the study. The analysis was conducted in accordance with the revised data of the learning effect, and the revision method is detailed in our previous study [32].

Table 2 lists the accuracy and revised speed of the cognitive test at different temperatures and time periods. There was no significant difference in cognitive performance at 26, 30, and 33 °C. The speed increased with exposure time at 37 °C, while the accuracy decreased. A significant difference in the Stroop test results was observed between different time periods ($p < 0.01$).

Table 2 also compares the cognitive performance at different temperatures during the same period. Forty-five minutes after beginning the experiment, the speed and accuracy at 37 °C were higher and lower than those of the other three conditions. The significance test indicated that the addition test completion speed during the final period (65–75 min) of the experiment at 37 °C was significantly higher than that at 26 °C ($p < 0.05$), and the visual react test completion speed at 37 °C was significantly higher than at the other temperatures ($p < 0.01$).

Table 2
Cognitive performance (mean ± SD) at different conditions during exposure under different period after correcting learning effect.

Outcomes	Period of time	26 °C	30 °C	33 °C	37 °C	Page test for trend ($p < 0.05$)
Stroop						
Speed	25–35min	30.3 ± 5.6	30.4 ± 5.0	32.1 ± 5.5	30.6 ± 6.9	–
(units/min)	45–55min	31.1 ± 6.0	31.7 ± 5.0	32.5 ± 5.0	31.3 ± 6.7	–
	65–75min	31.9 ± 4.7	31.6 ± 5.0	32.1 ± 5.2	32.7 ± 5.7	–
Accuracy (%)	25–35min	98.3 ± 1.9	98.2 ± 1.7	97.4 ± 3.2	97.9 ± 3.0	–
	45–55min	98.3 ± 2.2	97.5 ± 2.2	98.5 ± 1.7	97.1 ± 3.6	–
	65–75min	98.2 ± 2.4	98.1 ± 3.1	98.3 ± 1.5	$95.2 \pm 7.1^{abc**}$	–
Redirection						
Speed	25–35min	68.4 ± 13.7	67.3 ± 10.5	65.5 ± 11.5	66.4 ± 13.7	–
(units/min)	45–55min	65.7 ± 12.1	66.5 ± 11.3	65.9 ± 11.9	69.0 ± 14.8	–
	65–75min	67.0 ± 11.4	67.9 ± 12.5	67.6 ± 10.7	72.3 ± 20.1	–
Accuracy (%)	25–35min	96.1 ± 3.9	95.7 ± 3.9	95.7 ± 3.2	95.8 ± 4.1	–
	45–55min	95.4 ± 4.7	95.9 ± 3.7	95.6 ± 4.1	$93.0 \pm 9.3^{b*}{}_{1*}$	–
	65–75min	96.0 ± 3.7	94.8 ± 5.6	95.1 ± 4.5	$91.6 \pm 10.8^{abc*}{}_{1**}$	↓
Addition						
Speed	25–35min	6.5 ± 1.7	6.2 ± 1.6	6.7 ± 1.5	6.6 ± 1.8	–
(units/min)	45–55min	6.5 ± 1.6	6.5 ± 1.5	6.5 ± 1.6	6.7 ± 1.8	–
	65–75min	6.2 ± 1.5	6.5 ± 1.6	6.6 ± 1.6	$7.0 \pm 1.6^{a*}$	↑
Accuracy (%)	25–35min	92.6 ± 8.8	94.4 ± 7.3	94.2 ± 7.5	93.8 ± 7.3	–
	45–55min	94.0 ± 6.2	94.9 ± 7.6	93.5 ± 7.2	94.2 ± 6.5	–
	65–75min	95.1 ± 6.8	92.0 ± 9.2	93.3 ± 8.9	91.1 ± 8.4	–
Visual react						
Speed	25–35min	103.3 ± 14.7	102.0 ± 15.3	106.2 ± 18.4	103.9 ± 15.3	–
(units/min)	45–55min	103.0 ± 14.5	103.1 ± 13.1	103.0 ± 9.7	107.9 ± 15.0	↑
	65–75min	103.4 ± 14.8	105.1 ± 15.3	103.4 ± 12.3	$116.5 \pm 42.4^{abc**}$	–
Accuracy (%)	25–35min	96.3 ± 7.6	96.6 ± 5.2	95.0 ± 8.6	96.1 ± 5.7	–
	45–55min	96.7 ± 5.7	96.7 ± 5.6	97.2 ± 3.1	94.8 ± 7.1	↓
	65–75min	96.1 ± 5.7	95.4 ± 7.2	96.0 ± 4.9	93.9 ± 9.6	–
Tsai-Partington						
Speed	25–35min	15.4 ± 3.3	16.0 ± 2.2	16.1 ± 3.0	16.3 ± 2.2	–
(units)	45–55min	16.1 ± 2.9	16.8 ± 2.3	16.3 ± 2.5	16.8 ± 2.1	–
	65–75min	$16.9{\pm}2.1_{1**}$	17.0 ± 2.2	16.7 ± 2.1	16.5 ± 2.3	–
Accuracy (%)	25–35min	90.4 ± 14.8	89.6 ± 11.3	89.8 ± 12.6	89.0 ± 13.0	–
	45–55min	90.4 ± 13.1	91.3 ± 11.2	90.4 ± 11.8	87.8 ± 15.2	–
	65–75min	92.5 ± 11.6	91.9 ± 14.9	90.6 ± 12.8	89.4 ± 12.4	↓

Subscript letters indicated significant differences in post-hoc test between different periods. 1, 2 and 3 represent different period, respectively. Superscript letters indicated significant differences in post-hoc test between different conditions during exposure. a, b, c and d represent different temperature, respectively. Coding: 1: 25min–35min, 2: 45min–55min, 3: 65min–75min, a: 26 °C, b: 30 °C, c: 33 °C, d: 37 °C. d^{abc**} means that the cognitive test score of d has significant difference with a, b and c, respectively. 3_{12*} means that the cognitive test score of 3 has significant difference with 1 and 2, respectively. *$p < 0.05$. **$p < 0.01$.

Additionally, the accuracy of the Stroop and redirection test results at 37 °C and 65–75 min was significantly higher than that at the other temperatures ($p < 0.01$).

3.3. Physiological and subjective responses at increased temperatures

Table 3 lists the subjects' physiological and subjective responses immediately after completing the cognitive tests.

The physiological parameters changed significantly with exposure time. The tympanic temperatures and heart rate increased significantly ($p < 0.01$) with exposure time at 33 and 37 °C. pNN50 increased significantly ($p < 0.05$) with exposure time at 26 and 30 °C. At 37 °C, pNN50 was significantly lower ($p < 0.05$) at 65–75 min than that at 45–55 min. The subjective responses also changed significantly with exposure time. The thermal comfort ratings and acceptability of the thermal environment decreased with increasing exposure time, while the thermal sensation increased. There was a significant ($p < 0.05$) difference in the thermal sensation between 35-40 and 75–80 min. At 37 °C, the subjects reported an increase in the intensity of neurobehavioral symptoms with exposure time, stating that it was more difficult for them to concentrate and think clearly ($p < 0.01$). They were more fatigued ($p < 0.01$) and less alert ($p < 0.05$). The subjects also experienced severe headaches and dizziness ($p < 0.01$).

The measured physiological parameters and subjective responses significantly different between different periods. The tympanic temperatures, heart rate, and body weight loss increased significantly ($p < 0.01$) with increasing temperature, while pNN50 only decreased with increasing temperature at 65–75 min, and was significantly lower at 33 and 37 °C than at 26 °C($p < 0.01$). The thermal sensation increased progressively with temperature ($p < 0.01$) and thermal comfort rating, and acceptability of the thermal environment decreased significantly ($p < 0.01$) with increasing temperature. the alertness rating after 75 min decreased with increasing temperature, but only significantly differed ($p < 0.05$) between 26 and 37 °C. The fatigue ratings increased with increasing temperature. At 37 °C, the fatigue ratings were significantly ($p < 0.01$) higher with increasing temperature after 55 min than that at the other temperatures. After 55 min of exposure, the subjects reported that it was more difficult for them to concentrate and think clearly, and were experiencing severe headaches and dizziness. They were more fatigued with lower alertness. The ratings at 37 °C were significantly ($p < 0.01$) higher than those at the other temperatures.

Subscript letters indicated significant differences in post-hoc test between different periods. 1, 2 and 3 represent different period, respectively. Superscript letters indicated significant differences in post-hoc test between different conditions during exposure. a, b, c and d represent different temperature, respectively. Coding: 1: the first measured period of this parameter, 2: the second measured period of this parameter, 3: the third measured period of this parameter, a: 26 °C, b: 30 °C, c: 33 °C, d: 37 °C. d^{abc**} means that the parameter of d has significant difference with a, b and c, respectively. 3_{12*} means that the cognitive test score of 3 has significant difference with 1 and 2, respectively. *$p < 0.05$. **$p < 0.01$.

4. Discussion

The results of this study indicate that only the high temperature of

37 °C and relative humidity of 70% significantly affected the cognitive performance of the subjects after performing moderate-intensity activity for 45 min. The subjects' accuracy in all cognitive tests was lower at 37 °C than that at the other temperatures. Significant ($p < 0.05$) differences were observed in the accuracy of the subjects' responses to the Stroop and redirection tests between 37 °C and the other temperatures, which were employed to investigate the subjects' semantic interference, visual perception, and spatial positioning ability. Several studies have reported similar findings. Jiménez-Pavón et al. [10] stated that their subjects would complete visual-based cognitive tests with less accuracy after performing moderate-intensity activities under a temperature and relative humidity of 35 °C and 60%, respectively, for 60 min. Racinais et al. [8] also stated that the accuracy of their subjects' responses to cognitive tests related to visual memory decreased significantly after performing moderate-intensity activities under 50 °C for 10–15 min.

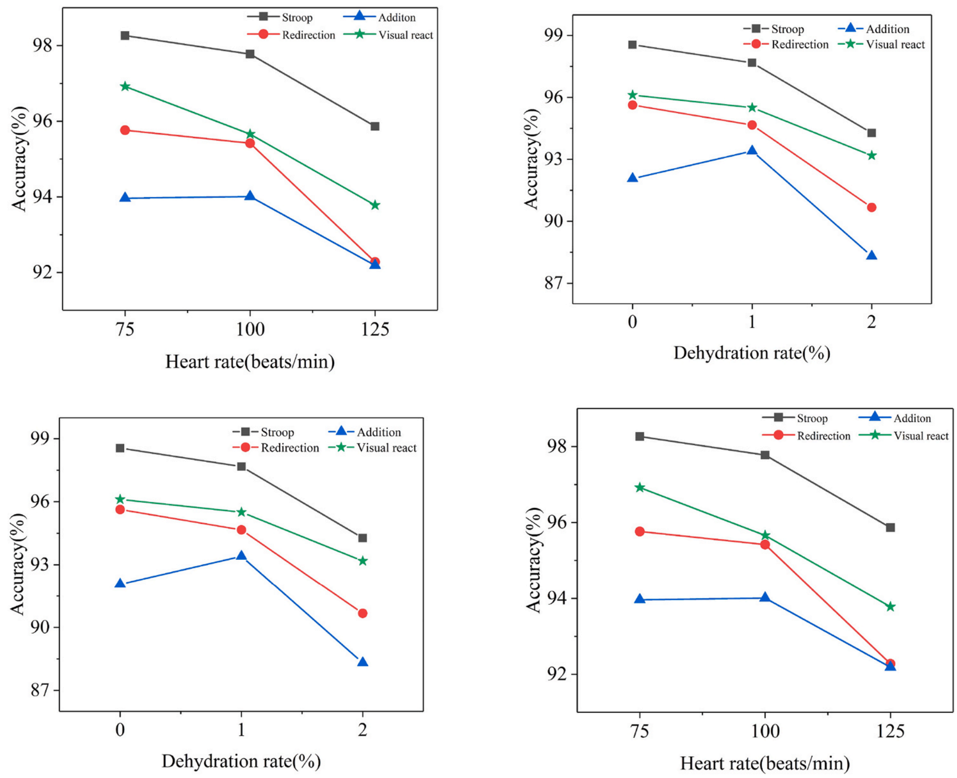
The decreased accuracy of the subjects' responses to the cognitive tests was associated with their physiological responses, thermal comfort, and neurobehavioral symptoms. Physiological responses, such as the tympanic temperature, heart rate, and dehydration rate, significantly increased at 37 °C, while the pNN50 was lower than that at 26 °C. Meanwhile, the subjects reported thermal discomfort, decreased alertness, and increased fatigue, accompanied by significantly more severe headaches and dizziness, and found it more difficult to concentrate and think clearly. These thermal responses indicate that a high temperature of 37 °C will increase the thermal stress on the human body [27], which will also affect the accuracy of their responses to the cognitive tests. As shown in Fig. 4a, the accuracy of the subjects' responses to the four neurobehavioral tests was related to the changes in the physiological parameters. The accuracy of the responses to the neurobehavioral tests tended to decreased with increasing tympanic temperature, heart rate, and dehydration rate. In all cognitive tests, excluding the visual react test, the accuracy of the subjects' responses gradually decreased with the decrease in pNN50. This can be proven by some existing studies that reported a decrease in the accuracy of responses to visual discrimination (RVP test), semantic judgment, and visual discrimination (Stroop test) tests were associated with increases in the core temperature or heart rate [28,33]. Additionally, when the dehydration rate exceeded 1% during exercise, the accuracy of the responses to memory, perceptual-motor coordination, thinking, and vision tests post-exercise was significantly correlated with the increase in the dehydration rate [5,6]. A decrease in pNN50 reflects a decline in the parasympathetic nerve tone, which may lead to a decrease in the accuracy of the subjects' responses to cognitive tests related to judgment and memory [34]. As the decrease in the parasympathetic tone was related to the impairment of prefrontal lobe nerve function [35], which is related to a series of cognitive functions, such as memory, judgment, analysis, thinking, and operation [36]. In addition to the physiological reactions, increases in the thermal discomfort and intensity of neurobehavioral symptoms also decreased the accuracy of the responses to neurobehavioral cognitive tests [28].

The subjects completed the cognitive tests faster at 37 °C. The speed of the completion of addition and visual reaction tests increased significantly at 37 °C ($p < 0.05$), which were conducted to investigate the subjects' thinking ability and ability to respond to visual signals, respectively. Some studies also concluded that the completion speed of cognitive tests, including the Stroop test, visual search, Sternberg working memory test, and Vienna test system, increased after performing high-intensity activities at– 33–35 °C [10,11]. The relationship between the physiological parameters and completion speed of the neurobehavioral tests is presented in Fig. 4b, which shows that the completion speed of the Stroop, redirection, and visual react tests increased with increasing tympanic temperature, heart rate, and dehydration rate. Previous studies also indicated that the increase in speed due to high temperatures may be related to the increase in the core temperature [24]. The subjects exercised sequentially at high temperatures, which resulted in a continuous increase in their sweat output and an increase in the dehydration rate. The increase in the dehydration rate may have also been related to the escalation in the response speed of the cognitive tests [6]. Additionally, exercising at higher temperatures may increase the arousal level and the level of hormones in the brain related to human arousal, such as norepinephrine and dopamine neurotransmitters, eventually leading to an increase in the cognitive test response speeds [37]. High temperatures appeared to improve the cognitive performance of the subjects performing moderate-intensity activities in terms of speed alone; however, a higher speed may also lead to decreased accuracy.

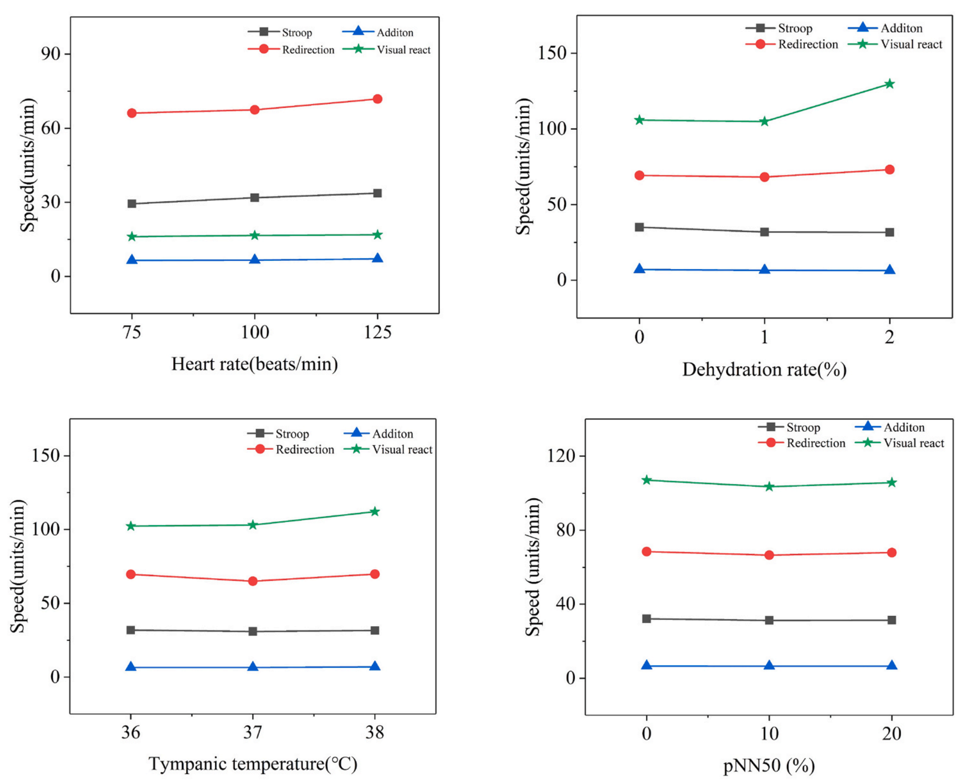
It was also found that the duration of exposure to a temperature of 37 °C affected the cognitive test scores. The longer the exposure, the faster they completed the cognitive tests, and the lower their accuracy. At 37 °C, the differences in the accuracy of the redirection test responses significantly differed between different periods ($p < 0.05$), which may have been due to the increasing thermal stress with exposure time, as indicated by the physiological parameters and subjective sensations at different times (see Table 3). Throughout the exposure periods, it was more difficult for the subjects to concentrate and think clearly. They also experienced thermal discomfort, decreased alertness, and increased fatigue, along with significantly more severe headaches and dizziness. Some studies also suggested that an elevated environmental temperature would lead to heat stress, which would then decrease the subjects' cognitive performance [38]. This is likely to be the main reason for the decline in accuracy over time. Moreover, as the exposure time in the experiment increased, the subjects were more likely to want to remove their physiological and psychological discomfort; therefore, they wanted to complete the experiment as quickly as possible. Such thoughts may actively increase the completion speed of these cognitive tests [39], but lead to more errors in the test responses and a decline in their accuracy.

Physiological strain index (PSI) carried out by Moran et al. can evaluate heat stress. This index could be calculated based on rectal temperature and heart rate. The higher PSI indicated the stronger heat stress. As shown in Table 4, PSI significantly increased with temperature ($p < 0.05$). In the same experimental condition, PSI significantly increased with exposure time. As previously mentioned, the accuracy of cognitive tests significantly changed with temperatures and exposure time. Fig. 5 exhibited the correlation between PSI and the accuracy of cognitive test, which indicated that the higher PIS lead to a lower accuracy of Stroop test and redirection test ($p < 0.05$). Therefore, heat strain could be a major reason why the score of cognitive tests changed with temperatures. What's more, Taylor et al. also suggested that the enhancement of heat strain was the reason why protective clothing could cause the reduction of cognitive performance [38]. To sum up, if the heat strain was strengthened, no matter it was caused by environmental temperature or experimental clothing, it may weaken the cognitive performance. Wearing protective clothing (elevated clothing thermal resistance) and conducting higher intensity activities would cause a higher risk of cognitive performance reduced, even in a lower temperature.

According to the results of this study, the reduction of the cognitive performance (accuracy) of people engaged in moderate-intensity labor prior to continuous exposure to a temperature 37 °C for 45 min can lead to a decline in the reliability of task completion, and even cause safety accidents [41]. Therefore, 45 min is recommended as the safe limit of continuous working time for moderate-intensity labor at 37 °C from the perspective of cognitive performance. The subjects' heart rates and tympanic temperatures did not exceed the physiological safety limit recommended by ISO9886 [18] after exposure to a temperature of 37 °C for 45 min. Considering physiological safety limits alone is insufficient to ensure safe operation at high temperatures. The initial cognitive performance decline due to high temperatures should receive more focus. In China, the municipal government of Shenzhen has stipulated a maximum continuous operation time at temperatures exceeding 35 °C, which is 2 h during summer [42], but without a theoretical basis. According to the results of this paper, a 2-h continuous operation time may



(a) physiological measurements versus accuracy.



(b) physiological measurements versus speed

Fig. 4. The effect of physiological measurements on cognitive performance.

Table 3
Subjective ratings of thermal environment (mean ± SD) and physiological measurements (mean ± SD) at different conditions during exposure under different period.

Outcomes	Period of time	26 °C	30 °C	33 °C	37 °C
Thermal sensation	35–40min	1.1 ± 0.9	$2.4 \pm 0.9^{a**}$	$3.1 \pm 0.6^{ab**}$	$3.4 \pm 0.6^{abc**}$
Very cold(-4) -	55–60min	1.2 ± 1.1	$2.5 \pm 0.8^{a**}$	$3.1 \pm 0.5^{ab**}$	$3.6 \pm 0.5^{abc**}$
Very hot(+4)	75–80min	$1.4 \pm 1.0^{12*}$	$2.5 \pm 0.8^{a**}$	$3.0 \pm 0.8^{ab**}$	$104 \pm 11^{abc**}{}_{1*}$
Thermal comfort	35–40min	1.00 ± 0.55	$0.60 \pm 0.61^{a**}$	$0.10 \pm 0.84^{ab**}$	$-0.57 \pm 0.95^{abc**}$
Very uncomfortable (−2) -	55–60min	0.90 ± 0.61	$0.52 \pm 0.65^{a**}$	$-0.01 \pm 0.74^{ab**}$	$-0.62 \pm 0.96^{abc**}$
Very comfortable (+2)	75–80min	0.91 ± 0.60	$0.50 \pm 0.65^{a**}$	$-0.03 \pm 0.75^{ab**}$	$-0.71 \pm 1.02^{abc**}$
Thermal acceptability	35–40min	0.50 ± 0.29	$0.30 \pm 0.35^{a**}$	$0.05 \pm 0.44^{ab**}$	-0.25 ± 0.48
Clearly unacceptable (−1) -	55–60min	0.50 ± 0.33	$0.29 \pm 0.34^{a**}$	$0.03 \pm 0.39^{ab**}$	$-0.27 \pm 0.51^{abc**}$
Acceptable (+1)	75–80min	0.51 ± 0.32	$0.30 \pm 0.37^{a**}$	$0.05 \pm 0.37^{ab**}$	$-0.32 \pm 0.54^{abc**}$
Alertness	35–40min	1.4 ± 1.1	1.3 ± 1.1	1.5 ± 0.8	1.4 ± 1.0
Very sleepy (−4) -	55–60min	1.5 ± 1.0	1.3 ± 1.1	1.4 ± 0.9	1.2 ± 1.0
Extremely alert (+4)	75–80min	1.6 ± 1.1	1.5 ± 1.0	1.2 ± 1.1	$0.9 \pm 1.3^{a*}{}_{12*}$
Fatigue	35–40min	28.6 ± 18.2	32.0 ± 17.5	34.3 ± 19.0	$38.1 \pm 20.1^{a*}$
Rested(0)-Tired(100)	55–60min	31.0 ± 19.9	33.0 ± 19.1	33.2 ± 18.9	$45.7 \pm 21.2^{abc**}{}_{1**}$
	75–80min	29.8 ± 17.3	30.2 ± 19.0	$37.9 \pm 20.6^{a*}$	$48.7 \pm 25.0^{abc**}{}_{1**}$
Headache	35-40min	13.4 ± 13.1	14.9 ± 15.7	12.6 ± 11.8	16.7 ± 17.7
No(0)-Severe(100)	55-60min	12.8 ± 14.7	14.4 ± 14.7	13.3 ± 14.3	$24.5 \pm 22.6^{abc**}{}_{1**}$
	75-80min	12.8 ± 12.8	12.9 ± 13.2	$16.5 \pm 15.4^{a*}$	$29.5 \pm 25.7^{abc**}{}_{1**}$
Dizzy	35-40min	19.2 ± 14.6	25.0 ± 17.2	25.5 ± 18.6	28.8 ± 22.7
No(0)-Dizzy(100)	55-60min	25.9 ± 20.7	24.1 ± 15.8	27.5 ± 21.0	$36.5 \pm 25.6^{abc**}$
	75-80min	20.8 ± 17.0	26.1 ± 19.0	$29.3 \pm 21.5^{a*}$	$41.5 \pm 29.0^{abc**}{}_{12**}$
Concentration	35-40min	24.8 ± 16.1	27.4 ± 15.7	29.0 ± 17.5	$36.7 \pm 20.9^{ac**}$
Easy(0)-Hard(100)	55-60min	27.7 ± 18.0	27.5 ± 15.6	32.5 ± 19.0	$40.9 \pm 22.7^{ab**}$
	75-80min	23.5 ± 13.8	27.7 ± 16.0	32.0 ± 18.7	$46.2 \pm 24.7^{abc**}{}_{12**}$
Thinking	35-40min	20.6 ± 14.3	23.1 ± 16.3	24.9 ± 17.2	28.5 ± 23.4
Clear(0)-Difficult(100)	55-60min	21.0 ± 17.2	21.8 ± 15.6	25.6 ± 19.2	$34.4 \pm 23.2^{abc**}$
	75-80min	20.1 ± 15.6	21.7 ± 16.4	25.0 ± 18.3	$37.4 \pm 25.6^{abc**}{}_{1**}$
Tympanic	35-40min	36.3 ± 0.2	$36.6 \pm 0.3^{a**}$	$36.9 \pm 0.3^{ab*}$	$37.5 \pm 0.3^{abc**}$
Temperature (°C)	55-60min	36.3 ± 0.3	$36.6 \pm 0.3^{a**}$	$36.9 \pm 0.2^{ab**}$	$37.9 \pm 0.3^{abc**}{}_{1**}$
	75-80min	36.3 ± 0.3	$36.6 \pm 0.3^{a**}$	$37.0 \pm 0.2^{ab**}{}_{12**}$	
Heart	25–35min	101 ± 10	102 ± 11	$107 \pm 14^{ab**}$	$121 \pm 14^{abc**}$
rate (beats/min)	45–55min	101 ± 10	$103 \pm 11_{1**}$	$110 \pm 13^{ab**}{}_{1**}$	$132 \pm 14^{abc**}{}_{1**}$
	65–75min	100 ± 11	$104 \pm 11^{a**}{}_{12**}$	$113 \pm 15^{ab**}{}_{12**}$	$141 \pm 15^{abc**}{}_{12**}$
pNN50 (%)	25–35min	2.1 ± 4.0	0.7 ± 1.1	3.4 ± 6.2	1.3 ± 2.8
	45–55min	2.2 ± 4.3	2.0 ± 4.3	2.0 ± 3.5	2.1 ± 3.9
	65–75min	9.8 ± 11.9	6.5 ± 12.2	$3.2 \pm 6.1^{a*}$	$0.6 \pm 1.2^{a**}$
Weight loss (kg)		0.329 ± 0.120	0.398 ± 0.131	$0.555 \pm 0.187^{a**}$	$0.805 \pm 0.324^{ab**}$
Dehydration rate (%)		0.56 ± 0.13	0.67 ± 0.13	$0.95 \pm 0.18^{ab**}$	$1.39 \pm 0.49^{abc**}$

Table 4
PSI (mean ± SD) at different conditions during exposure under different period.

Period	26 °C	30 °C	33 °C	37 °C
25–40min	0.54 ± 0.36	$0.99 \pm 0.42^{a*}$	$1.67 \pm 0.7^{ab**}$	$3.22 \pm 0.84^{abc**}$
45–60min	0.56 ± 0.41	$1.14 \pm 0.44^{a**}{}_{1*}$	$1.91 \pm 0.67^{ab**}$	$4.47 \pm 0.84^{abc**}{}_{1**}$
65–80min	0.55 ± 0.43	$1.2 \pm 0.5^{a**}{}_{1**}$	$2.21 \pm 0.77^{ab**}{}_{1*}$	$5.32 \pm 1.17^{abc**}{}_{12**}$

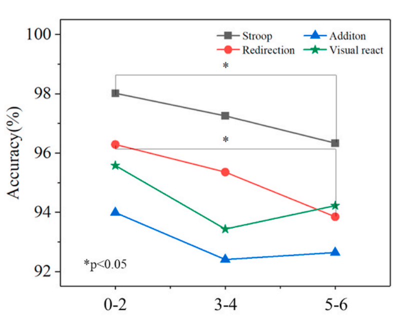


Fig. 5. The effect of PSI on cognitive performance.

be too long.

The experimental methods used in this study differ to those used in previous work. First, the subjects completed all of the cognitive tests while maintaining moderate-intensity exercise. However, in most previous studies, the subjects were required to complete cognitive tests after exercise, which does not fully reflect the impact of moderate activity. Second, before conducting the formal experiment, practice sessions were conducted for 2 d, during which the cognitive tests were administered reduplicatively. Combined with the formal experimental results, the new correction method proposed by the authors [32] was adopted to modify the test, and the learning effect remained. Such correction can minimize the influence of learning effects on the analysis results and ensure the reliability of the experimental results. A sufficient number of exercises were not conducted in previous studies; therefore, the learning effect was eliminated.

The subjects of this study were college students without heat acclimation. Some studies suggested that temperatures of over 40 °C would not significantly affect cognitive performance. However, these studies involved occupational staff who had undergone heat acclimation training or were used to operating at high temperatures [13,14]. Therefore, the applicability of the results of this study still needs to be verified by experiments involving high-temperature operators. Another limitation of this study is that the subjects of the study were college-age students who had higher education (or are in the process obtaining the same). To improve the theoretical system in the field, more subjects of a wider age range and education levels should be included in future studies. But for the construction workers on site who did not have higher education would make more mistake during working under high temperature [43]. Therefore, their damage of cognitive performance caused by high temperature may be severe. In the further experiment, cognitive tests should be conducted in more periods in longer experimental time, which helps to confirm the exact time that cognitive performance reduce. In addition, the experiments in this study did not involve temperatures above 37 °C, and the relative humidity was maintained at 70%. More experiments with higher temperatures, higher humidity, and different activity intensities will be conducted to further develop new safety limits for high-temperature operation based on the cognitive performance of personnel.

5. Conclusions

In this study, moderate-intensity exercise was simulated by walking on a treadmill at 4 km/h, and the estimated metabolic rate was 165 W/m^2. The effect of increases in temperature on the cognitive performance was analyzed under the simulated environment of a climate chamber at 26, 30, 33, and 37 °C, with a relative humidity of 70%. The main conclusions are as follows:

(1) The subjects exercising with moderate intensity at 37 °C tended to complete the cognitive tests faster as the exposure time increased, while their accuracy declined. The completion speed was higher than that at 26, 30, and 33 °C, while the completion accuracy was lower. Cognitive tests were conducted to investigate the subjects' semantic interference, visual perception, spatial positioning ability, responses to visual signals, thinking, and arousal level. There was no significant difference in the cognitive test scores between the 26, 30, and 33 °C conditions.
(2) At 37 °C, the tympanic temperature, heart rate, and dehydration rate were significantly higher than those at 26, 30, and 33 °C, while pNN50 was lower. Meanwhile, the subjects experienced thermal discomfort, decreased alertness, and increased fatigue, with significantly more severe headaches and dizziness. It was also more difficult for them to concentrate and think clearly. At 37 °C, as the exposure time increased, the subjects' physiological and subjective reactions also showed a similar trend.
(3) The completion accuracy of the neurobehavioral cognitive tests during moderate-intensity activity decreased as the tympanic temperature, heart rate, and dehydration rate increased. The accuracy decreased as pNN50 decreased, while the speed increased.
(4) Based on the decreased accuracy with exposure time, 45 min is recommended as the safe duration for continuous work involving moderate-intensity labor at 37 °C.

The results showed that the cognitive performance of subjects undergoing moderate-intensity activity was impaired by the high temperature of 37 °C, but their physiological parameters did not reach the safe limit. Therefore, a new safety limit for high-temperature operation from the perspective of cognitive performance should be established.

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.

Acknowledgements

This project was supported by the National Natural Science Foundation of China (Grants No. 51778625 and 51478471) also supported by Fundamental Research Funds for the Central Universities of Central South University (Grants NO. 2020zzts514). The neurobehavioral tests battery was provided by Prof. Zhiwei Lian and Dr. Li Lan from Shanghai Jiaotong University in China. The authors have also appreciated the subjects who volunteered for this survey.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.buildenv.2020.107372.

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