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ARTICLE

Changes in EEG signals during the cognitive activity at varying air temperature and relative humidity

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Abstract
In this study, we examined changes in EEG signals during the cognitive activity at different air temperatures and relative humidities (RH). Thirty-two healthy young people acclimatized to the subtropical climate of Changsha, China, were recruited as subjects. They experienced four air temperature levels (26, 30, 33, and 37 °C) and two relative humidity levels (50 and 70%) in a climate chamber. During 175 min-long exposures to each thermal condition, they performed cognitive tasks and their EEG signals were measured. Relative humidity of 70% and increased temperature at this relative humidity significantly increased the relative power of δ-band and significantly decreased relative power of θ-band, α-band, and β-band. This may suggest that subjects were more sleepy but less drowsy, and it was more difficult for them to think clearly. At the same time, subjective evaluations indicated that they could be less alert and it was harder for them to think. However, no changes in performance of tasks measuring cognitive abilities were observed. It remains therefore unclear whether EEG can be a credible marker of changes in cognitive activity as a result of changes in indoor environmental quality in buildings and the future experiments should closely examine this issue.

Keywords Air temperature · Relative humidity · Performance · Electroencephalogram (EEG)

Introduction

Electroencephalogram (EEG) is an electrophysiological monitoring method to record the electrical activity of the brain. It is typically noninvasive with the electrodes placed along the scalp, although invasive electrodes are sometimes used such as in electrocorticography. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain [1]. EEG records four periodic rhythms (bands): delta (δ), theta (θ), alpha (α), and beta (β). They are characterized by different frequencies, as follows: δ by 1-4 Hz, θ by 4-8 Hz, α by 8-14 Hz, and β by 14-30 Hz. δ-band is primarily related to sleep, θ-band is related to drowsiness, α-band is often present in relaxed awareness without attention, and β-band is related to active thinking [2]. He et al. [3] used EEG to assess sleep quality. EEG oscillation can be the result of neuromodulation via pharmacology, rhythmic sensory stimulation/steady-state-evoked potentials; EEG-neurofeedback; repetitive transcranial magnetic stimulation; and transcranial alternating current stimulation [4].

Previous studies measuring human brain activity that utilized positron emission tomography or functional magnetic resonance imaging have shown that heat signals from the skin can reach the cerebral cortex [5–7]. They thus suggest that responses of human to the thermal environment can be reflected by EEG signals. However, only a few studies have documented the impact of thermal environment on EEG. Lv et al. [8] compared the EEG signals of 19 college students at 25 and 32 °C; during EEG measurement, the subjects were instructed to select a comfortable posture on the chair with their eyes open. The study showed significantly higher δ-band activity (related to sleepiness) at 32 °C, while no significant difference was found between the two different ambient temperatures for the other EEG bands. Yao et al. [9] measured the 10-min-long EEG signals of 20 healthy students at four ambient temperatures: 21, 24,

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26, and 29 °C. During data collection, the subjects were asked to stay relaxed with their eyes closed and to clear their mind. The results show that relative EEG power of β-band (related to active thinking) was significantly higher under 21 and 29 °C compared with 24 and 26 °C.

Thermal environment in buildings has been documented in many studies to be an important variable that influences comfort, well-being, health, and performance of building occupants [10–14]. Few mechanisms were put forth to explain why changes in the thermal environment have negative effects on humans [15–18]. In addition, several studies measured physiological responses as a result of changes in thermal conditions [9, 19, 20]. Among others, it was observed that skin temperature follows the changes in temperature [21, 22]. However, none of these studies used EEG to examine whether changes in the thermal environment would produce measurable changes in EEG. Since EEG is thought to be related to various sensory and cognitive processes [23–25], it is reasonable to expect that changes in the thermal environment affecting human performance would cause measurable changes in EEG signals. If EEG signals change this could provide evidence and explanation to why the cognitive performance of humans is reduced at moderately increased indoor temperatures or when thermal discomfort is experienced [26, 27]. Consequently, measured EEG signals could support the present knowledge showing how changes in the thermal environment affect human cognitive performance.

One reason why EEG was not widely used in previous studies was most likely its complicated measurement. It was performed usually in the specialized labs requiring shaving of the head to place the sensors on the head, all making the conditions and context highly different from what is experienced in buildings. In addition, the cost of instrumentation to measure EEG and its sensitivity to numerous disturbances such as rapid movement of the head limited its widespread use. With the rapid development of instruments allowing quick and fairly simply a measurement of physiological responses of humans, the new instruments for measuring EEG signals became available [28–30]. This made it possible to use EEG measurement in indoor air research. This study presents such an application of EEG monitor in which experiments were performed examining the effect of temperature and relative humidity on brain activity during simulated work in the laboratory.

Methods

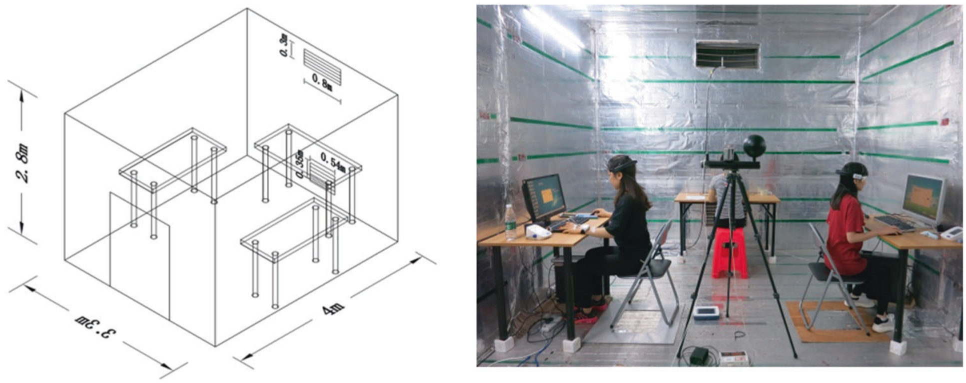
Experiment

Two experiments were carried out. Experiment 1 was completed in August and September of 2016, while experiment 2 was completed in October and November of the same year. In both experiments, four temperatures were examined, respectively, 26, 30, 33, and 37 °C but at two levels of relative humidity, 70% in experiment 1 and 50% in experiment 2. The reason for this was the possibility to reach high humidity levels in the chamber (in Changsha, outdoor humidity is high in summer and low in autumn/winter). In order to reach the intended level of relative humidity of 70% in the chamber, it was necessary to perform experiments with that level of relative humidity first, i.e., during late summer when the outdoor humidity level was still high. As a result, two experimental blocks were created with relative humidity of 70 and 50% causing randomization restriction, which made it impossible to examine the interaction between relative humidity and temperature. All other parameters remained unchanged: The measured intensity of illumination was 147.4 ± 24.4 lx, outdoor air rate at which chamber was ventilated was at 1000 m^3/h (air change rate was at 27 h^{-1}), and the concentration of CO_2 during experiments was close to the ambient level of 400 ppm the average air velocity in the chamber was kept below 0.1 m/s.

Experiments were conducted in a climate chamber with dimensions of 3.3 m × 4 m × 2.8 m (W × L × H) at the Central South University in Changsha, China (Fig. 1). Three workstations were established in the chamber, two for subjects participating in the experiments and one for the experimenter. Each workstation consisted of a chair, a table, and a computer. The chamber was ventilated with 100% outdoor air through a 0.8 m × 0.3 m inlet located on the side wall. The air temperature and humidity in the chamber were maintained by controlling parameters of the air supplied to the chamber. The chamber had no windows.

Thirty-two subjects were exposed to each condition in groups of two following the Latin square design. Separate Latin square design was used in experiment 1 and experiment 2. The exposure during each condition lasted 175 min and each subject experienced eight different conditions created in the chamber. Experimenters were blind to the condition experienced by the subjects; they remained also blind when analyzing the results.

During experiments, the subjects performed neurobehavioral tests to assess the effect of conditions on their cognitive performance. These tests were performed three times during exposure and each lasted 30 min. EEG signals were measured only during the first presentation of neurobehavioral tests. In addition, several physiological parameters were monitored along the course of experiments to observe responses of subjects to different conditions in the chamber. They included measurements of eardrum temperature, skin temperature and moisture, heart rate, end-tidal carbon dioxide, and arterial blood oxygen



(a) (b)

Fig. 1 The chamber where the experiments were carried out

saturation. Subjects rated moreover their comfort and indicated any perceived acute health symptoms. This paper focuses mainly on EEG signals subjective responses and cognitive performance. Other responses were reported by Fan et al. [31].

Subjects

The subjects were 32 healthy Chinese college-age students (Table 1), 16 females and 16 males. None of the subjects had a history of cardiovascular disease, hypertension, and hyperglycemia. The body mass index (BMI) of the subjects was in the normal range for the equivalent Chinese population (18.5–23.9 kg/m^2). All subjects lived in Changsha for at least one year prior to the commencement of experiments. The number of subjects was determined using power analysis to ensure adequate power for detecting statistically significant differences between the conditions at the level of $P < 0.05$. The minimum number of subjects required was estimated with G*power software to be 25 persons.

Subjects were told not to sleep late and drink alcohol or caffeine 24 h prior to the experiment. Females participating in the experiment were not in their menstrual cycle during exposures. Two days prior to experiment 1, the subjects turned up in the laboratory to rehearse experimental procedure and perform tests similar to those used during exposures in the chamber; neurobehavioral tests were practiced ten times on 2 consecutive days. Practice and rehearsal were performed at the air temperature of 26 °C and without control of the relative humidity. During this session, the subjects adjusted their clothing until they felt thermally neutral. They were then asked to use the same garment parts during the entire exposure experiment. It included a t-shirt, thin trousers, sports shoes, socks, and underwear yielding the clothing insulation of about 0.39 clo. Subjects were paid the salary on a fixed hourly basis without any bonus.

Table 1 Details of the subjects participating in experiments

Information	Mean ± SD
Total number of subjects	32 (16 females and 16 males)
Age (years)	23 ± 2
Height (cm)	167 ± 9
Weight (kg)	56.7 ± 10.3
Occupation	Undergraduate (9) and graduate (23)
BMI	20.1 ± 2.4
Number of smokers	0

Experimental conditions

Two relative humidity levels: 50 and 70%, and four temperature levels: 26, 30, 33, and 37 °C were studied. The rationale for choosing these conditions is provided by Fan et al. [31], which is summarized briefly below.

The temperature of 26 °C was designed as a neutral condition. According to Chinese standards [32], it is the lower limit of air conditioning for public buildings in summer too.

A temperature of 30 °C was chosen as it may cause heat stress: hypothalamus is expected to begin regulating body temperature at this temperature level [33].

A temperature of 33 °C was chosen because it is used as a temperature level above which employers must pay "high-temperature subsidies" to their employees, in China [34]. It also represents the average skin temperature of people who rest in a comfortable environment [35, 36].

A temperature of 37 °C is close to the core temperature of the normal human body [33]. In China, an outdoor temperature of 37 °C is the level of action for a high temperature "orange warning" alarm [37], which means that when maximum temperature rises above 37 °C within 24 h, warning must be sent out to people to avoid outdoor activities to pay attention to heatstroke prevention.

The relative humidity of 50% was selected because it was suggested as a lower limit of thermal comfort in some tropical countries [38].

The relative humidity of 70% is usually recommended as the upper limit of thermal comfort in hot and humid environments [39, 40] and it is common indoors in tropical and subtropical climates [41–43].

Measurements

Measurements of physical parameters

The air temperature, relativity humidity, illumination, and CO_2 concentration in the chamber were continuously measured by HOBO data loggers (Onset Computer Corp., Bourne, MA, USA). All physical parameters were measured at the center of the chamber with the frequency of once per minute. All the instruments were calibrated. The accuracy and specifications of all instruments are listed in the supplementary material (Appendix 1).

Measurements of EEG

EEG was measured using the $EPOC^+$ headset (EMOTIV Inc., USA); this system was previously used in other studies, e.g., see [2]. The EMOTIV $EPOC^+$ features 14 EEG channels plus two reference channels (CMS and DRL) offering optimal positioning for accurate spatial resolution. The 14 channels are located at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4 according to the international 10–20 system [44] as shown in Fig. 2. These fourteen channels are located in the three main areas of the brain, the frontal lobe (AF3, F7, F3, FC5, FC6, F4, F8, and AF4), temporal lobe (T8 and P8), and occipital lobe (P7, O1, P8, and O2). The sampling frequency was 128 Hz (1 per 0.0078 s). All felt pads on top of the sensors of 14 channels were adequately wetted with the salt solution to ensure proper electrical conductivity with the scalp. $EPOC^+$ headset was put on the subjects' heads with the help of experimenter to ensure that it was sitting correctly and all electrodes had proper contact.

The signals measured by $EPOC^+$ were recorded by the EmotivPRO software especially built for the $EPOC^+$ headset. The software allows viewing sensor data in real time and saves the EEG data for the subsequent processing.

The data recorded by EmotivPRO software were subsequently loaded into Matlab for further processing.

Measurements of cognitive performance

The neurobehavioral battery comprising six computerized cognitive tests was used to measure the cognitive performance of the subjects at different conditions in the chamber. They included: Stroop, which is examining the semantic thinking and visual perception; redirection examining spatial orientation test; overlapping examining spatial reasoning ability and perception of target stimuli; addition examining mental arithmetic ability; multiplication examining mental arithmetic ability; and visual learning examining spatial working memory. The details of the tests can be found in Liu et al. [45–47].

All six tests took 30 min to complete. The number of test questions for each type of test was as follows: 145 Stroop tests, 200 redirection tests, 15 overlapping tests, 25 addition tests, 20 multiplication tests, and 6 visual learning tests. All the test questions could be completed in less than 30 min. The subjects who completed them in less than 30 min performed visual reaction time test to make sure that the full 30-min period is completely used for measuring cognitive performance. The details of visual reaction time test can be found in Liu et al. [45]. The speed and accuracy to complete the tests were used as measures of performance of tests.

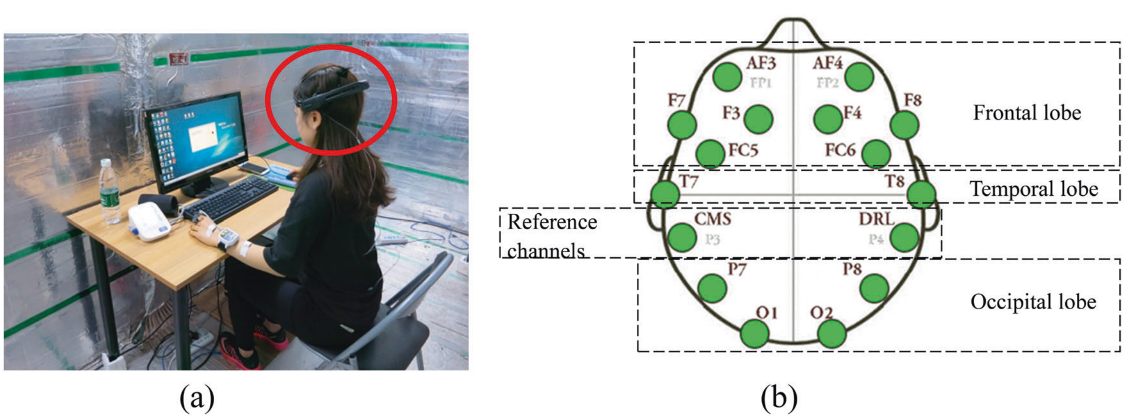


Fig. 2 Measurements of EEG signals: **a** EEG acquisition with EPOC + headset. **b** Locations of electrodes on the scalp

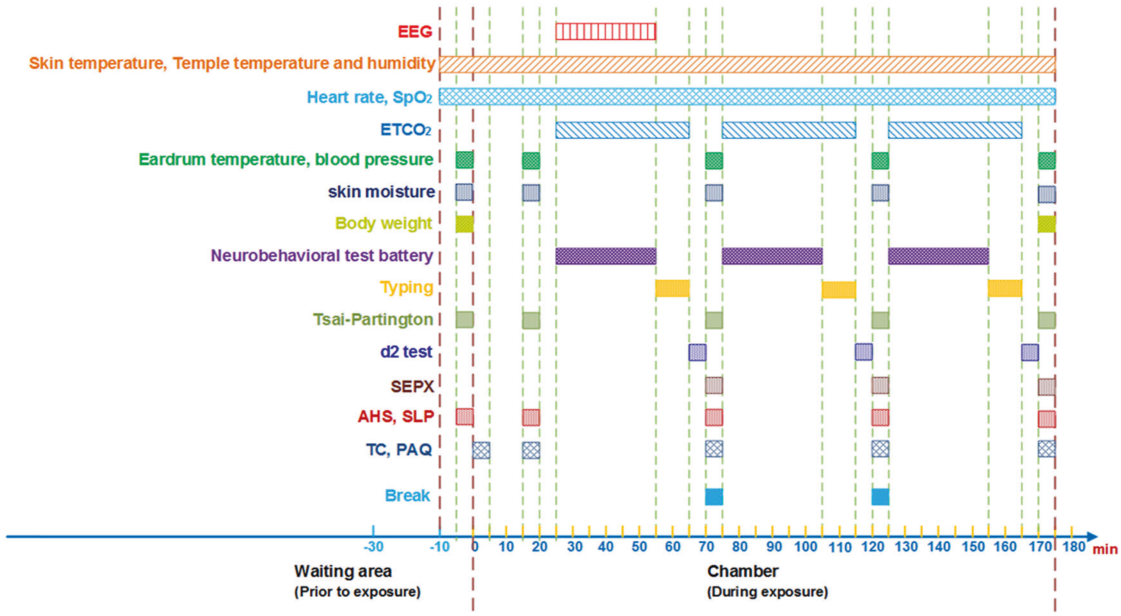


Fig. 3 Experimental procedure

Subjective measurements

Subjective responses were collected using paper-based questionnaires. They included questions regarding thermal comfort, thermal sensation, and acceptability (TC); perceived air quality (PAQ), acute health symptoms (SBS); self-estimated work performance (SEPX); and self-estimated sleepiness (SLP). Considering the hot and humid conditions in the experiment, the 9-point extended scale introduced by ISO 10551 [48] was used to measure thermal sensation rather than the 7-point scale of ASHRAE [49]. The details of all scales can be found in the paper by Fan et al. [31].

Experimental procedure

The subjects were divided into eight groups of four. Each group was composed of two females and two males. Subjects were exposed in the chamber in pairs of the same gender. Each day one group participated the first pair from 13:00 to 15:55 and the second one from 16:30 to 19:25, always at the same time of day at different conditions. Each group experienced all four conditions in experiment 1 and in experiment 2 on four consecutive days. Each exposure was 175 min in length.

The subjects were not informed about exposure conditions in each experiment. During exposures, they were not allowed to move around or talk to each other. They could drink water during the break (see Fig. 3) and before the experiment. They were additionally informed that they could quit experiments at any time if they felt unwell or did not want to continue; nobody quit during experiments.

The experimental procedure is shown in detail in Fig. 3. Before each exposure, the subjects stayed in the waiting room for about 30 min where the air temperature was kept at about 26 °C and the relative humidity was not controlled. They could consume water and snack. Then the body weight measured for the first time. When in the waiting room the subjects completed questionnaire collecting information on their activities prior to experiments with respect to sleep, beverages and food consumed, medicine taken, and physical activity. Once 30 min passed the subjects entered the climate chamber, where they stayed for 175 min. EEG was measured after 25 min from the onset of exposure. The measurement took 30 min and was paralleled with the neurobehavioral tests. In the pilot experiments, EEG measurements were performed more than once but subjects reported feeling uncomfortable when wearing EEG acquisition equipment for too long time. This is why EEG measurements commenced only once. The details of $ETCO_2$, SpO_2, SEPX, AHS, SLP, TC, and PAQ in the study can be found in Fan et al. [31].

The study followed the guidelines of the Declaration of Helsinki [50] and was approved by the relevant Ethics Review Board of the First Hospital of Hunan University of Chinese Medicine (AF/SC-07/02.0). Oral and written informed consent to participate in the experiments was obtained from each subject.

EEG data processing

EEG data preprocessing

EEG data preprocessing was performed with EEGLAB toolbox (version14.0.0) [51] running under the Matlab environment. The artifacts were removed firstly by the visual inspection when scrolling through the data. The frequency range of EEG studied in this paper is 1–30 Hz, so the waves below 1 Hz were filtered out using a filter to remove the low-frequency noise, and the waves above 30 Hz were filtered out using a filter to remove high-frequency noise. Artifacts such as eye blinks and muscle activities were removed by running the independent component analysis (ICA) algorithm in EEGLAB [2]. For example, the EEG contaminated with electrooculogram (EOG) artifacts is input to ICA. The ICA separates the EEG and EOG components. ECG component is rejected by the EEGLAB automatic EEG artifacts detector: ADJUST (ADJUST1.1.1) [52]. (See Appendix 7 for details).

EEG data processing

Brain activity was quantified by the relative power of four EEG bands in different frequency ranges. The artifact-free EEG data were processed with Matlab bandpower function to obtain the relative power for four frequency bands: δ, θ, α, and β, where the relative power is the ratio of the power of each band to the total power of the four bands. The process was conducted on 14 EEG channels, respectively, i.e., the relative power of the four bands on each channel was calculated, respectively (Code availability: see Appendix 8 in the supplementary material for code details). The obtained relative EEG power of four bands at different exposure conditions was used in the statistical analysis.

Statistical analysis

Because of restriction on randomization of relative humidity, one-way ANOVA analysis was used to examine the main effect of temperature; repeated measures ANOVA was used to examine the main effect of relative humidity, the level of each temperature being regarded as repetition. All analyses were within-subject analyses, i.e., each subject was his/her own control.

One-way ANOVA was used to examine the main effect of temperature in the two experiments separately. Bonferroni method was used for the post hoc comparison. The temperature was used as an independent variable, and subjective responses speed and accuracy at which different performance tests were performed were dependent variables. For EEG signals, ANOVA was conducted on the relative EEG power.

Repeated measures ANOVA was used to examine the main effect of relative humidity, the level of each temperature was regarded as repetition, i.e., subjective responses speed and accuracy at each temperature level were used as the within-subject variable, and relative humidity was used as a between-subject factor. For EEG signals, ANOVA was conducted on the relative EEG power.

The statistical analysis was performed on four frequency bands and 14 EEG channels.

All statistical analyses were performed using SPSS v22.0 (SPSS Inc., Chicago, USA), and significance was set at $P < 0.05$ (two-tail).

Results

Descriptive statistics for all outcomes, including means and standard deviations, are shown in the supplementary material.

Physical parameters

Table 2 shows the intended and measured temperatures and relative humidities. It is clear that the intended levels were reached; temperature deviation did not exceed 0.3 °C while relative humidity was within ±2% of the intended levels.

Thermal sensation and thermal acceptability

Subjective votes concerning thermal environment made just before and just after EEG measurements were consistent and not significantly different from each other at each of the eight examined conditions in the chamber. They were consequently averaged (see Appendix 2, Table A in the supplementary material). The temperature had a significant impact on thermal sensation and thermal acceptability, while relative humidity had no effect on thermal sensation and thermal acceptability. Subjects felt thermally neutral at 26 °C (Fig. 4). They felt hot when the temperature reached 37 °C; at this temperature, the subjects felt thermally unacceptable. Although no significant effect of humidity

Table 2 Mean ± SD temperatures and relative humidities at different experimental conditions in the chamber

Targeted temperature and RH		Monitored temperature and RH	
Temperature (°C)	Relative humidity (%)	Temperature (°C)	Relative humidity (%)
26	50	26.2 ± 0.0	51 ± 1
30		29.9 ± 0.1	50 ± 0
33		32.8 ± 0.1	51 ± 1
37		36.7 ± 0.1	51 ± 1
26	70	26.3 ± 0.1	69 ± 2
30		30.0 ± 0.2	70 ± 2
33		32.9 ± 0.2	72 ± 1
37		36.8 ± 0.1	72 ± 2

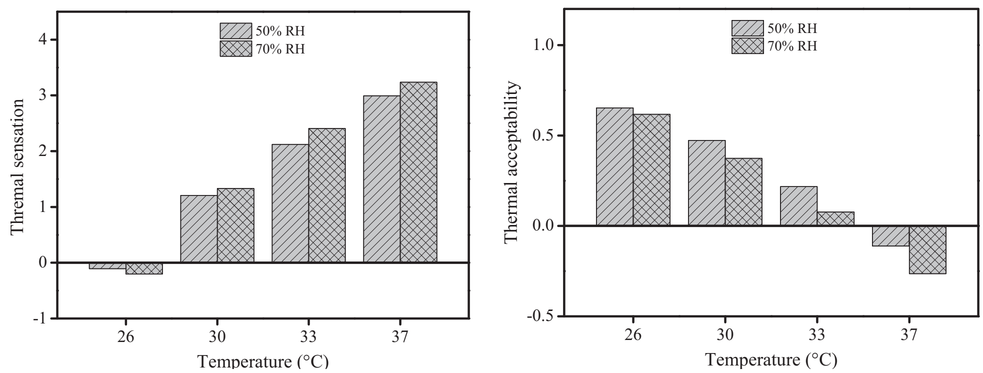


Fig. 4 Thermal sensation and thermal acceptability at different experimental conditions

was examined, at temperatures of 30, 33, and 37 °C subjects reported feeling hotter when relative humidity was 70% than when it was 50%. Furthermore, they reported feeling thermally more unacceptable when relative humidity was 70% than when it was 50% at all temperature levels. The scales of thermal sensation and thermal acceptability are provided in Appendix 2 in the supplementary material.

Neurobehavioral tests

The performance of neurobehavioral tests performed along the measurements of EEG (i.e., between the 25th and the 55th minute from the onset of exposure) is shown in Figs. 5 and 6. The temperature did not have a significant effect on performance, while relative humidity of 70% reduced the speed at which the tests were performed and for some tests accuracy compared to speed and accuracy at 50%. Mean values and standard deviations of speed and accuracy are shown in Appendix 3 in the supplementary material.

Electroencephalogram

Mean values and standard deviations of relative power for four EEG bands are shown in Appendix 4 (supplementary material). The main effect of temperature was observed almost only at 70% RH, and it was seen on 13 out of 14 channels for δ-band, on 11 out of 14 channels for α-band and β-band, and on 8 out of 14 channels for θ-band. The main effect of relative humidity was observed on all 14 channels for δ-band and θ-band, on 12 out of 14 channels for α-band and on 9 out of 14 channels for β-band. (Appendix 4, Table E and see Fig. 8).

The effect of temperature on EEG relative power

Figure 7 summarizes the results of the post hoc test between different temperatures; it shows the effect of increased temperature on the relative power of EEG bands. The significant change in EEG power occurred mainly at 37 °C at which the relative power of δ-band increased significantly, while for the other three bands it decreased significantly. This effect was mainly occurring at a relative humidity of 70% and at a temperature of 37 °C compared with 26 and 30 °C. This result may suggest that to obtain the effect on EEG the change in temperature must be relatively strong (33 °C versus 26 °C). With increasing temperature, the number of channels that changed significantly also increased. Only one channel was significantly changed at a relative humidity of 50% and at a temperature of 37 °C compared with 30 °C, this is most likely due to random responses, because there was no significant difference between 37 and 26 °C when relative humidity was 50%.

The effect of relative humidity on EEG relative power

Figure 8 summarizes the results of the main effect of humidity on the EEG relative power. The relative power of δ-band (primarily representing sleep) increased significantly at a relative humidity of 70%, while the relative power of θ-band, α-band, and β-band decreased significantly at this humidity compared with these at a relative humidity of 50%.

Results of the frontal lobe, temporal lobe, and occipital lobe

The three cortexes—frontal, temporal and occipital—are functionally specialized. Frontal lobe area is considered to play an important role in cognitive functions [53–55]. In addition, Nielsen et al. [56] suggested that fatigue during heat stress is related to changes in frontal cortex brain activity. The temporal lobe is thought to be associated with perception and recognition of auditory stimuli and memory, while occipital lobe is linked with many aspects of vision [57, 58]. Consequently, the analysis was done targeted on these three cortexes. EEG data were averaged for the three cortexes and statistical analysis repeated. The results are shown in the supplementary material (Appendix 5) and they are similar to the results presented in Figs. 7 and 8. They show that the effect of temperature on EEG occurred only at

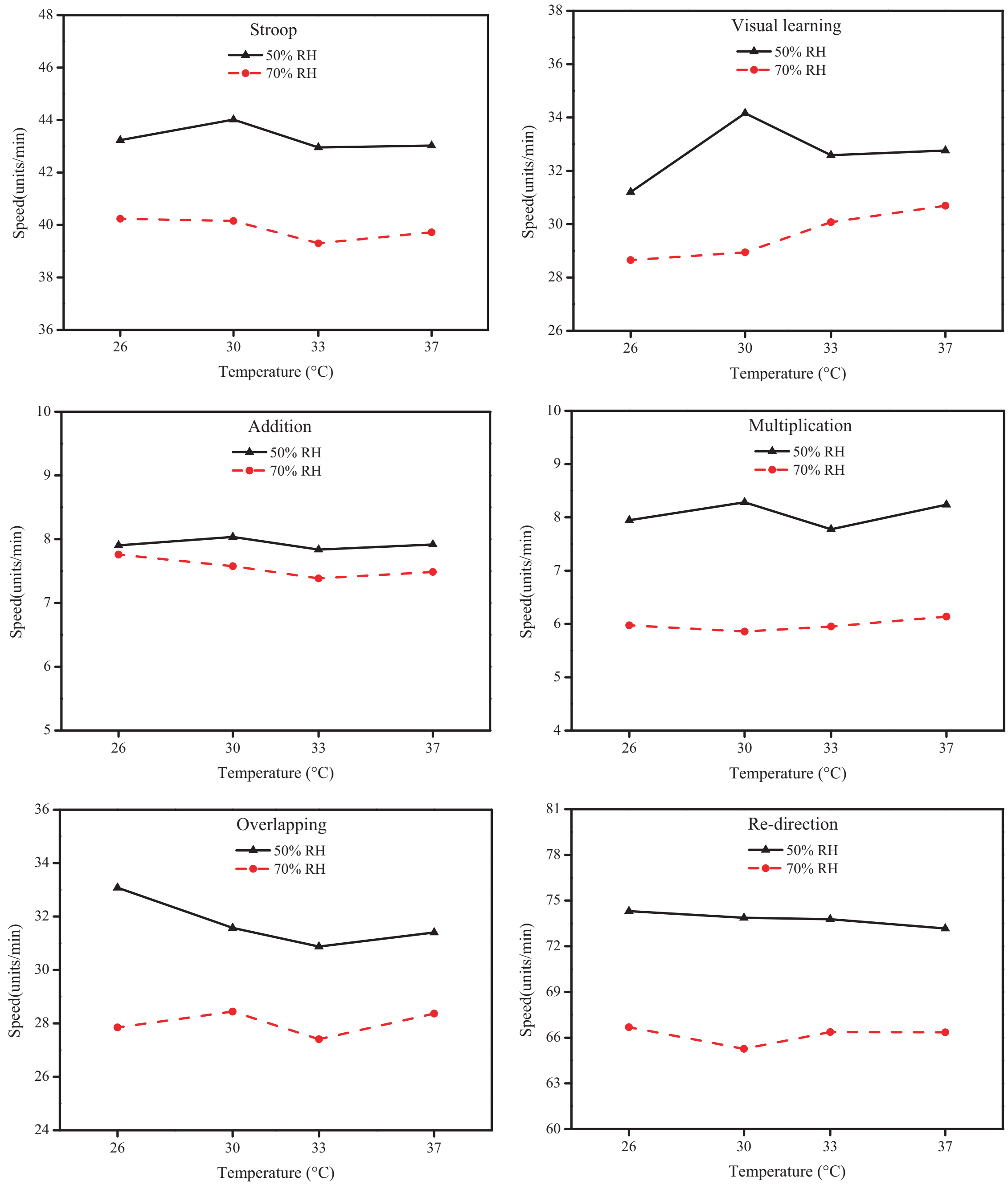


Fig. 5 Speed at which different neurobehavioral tests were performed at a different temperature and relative humidity levels

a relative humidity of 70% and generally, when the temperature reached 37 °C. Increasing temperature caused the relative power of δ-band to increase significantly, while the relative power of θ-band, α-band, and β-band decreased significantly. No significant effect of temperature on θ-band in temporal lobe was observed. Increasing relative humidities (RH) had the same effect as the increasing temperature on the four EEG bands, i.e., increasing humidity caused relative power of δ-band to increase significantly, while the relative power of the other three bands decreased significantly. Moreover, RH affected all the three cortexes and all four EEG bands.

Discussion

Present results show that EEG signal changed mainly at two levels of relative humidity. The changes were seen for all bands and indicated increased sleepiness and reduced drowsiness, awareness without attention, and active

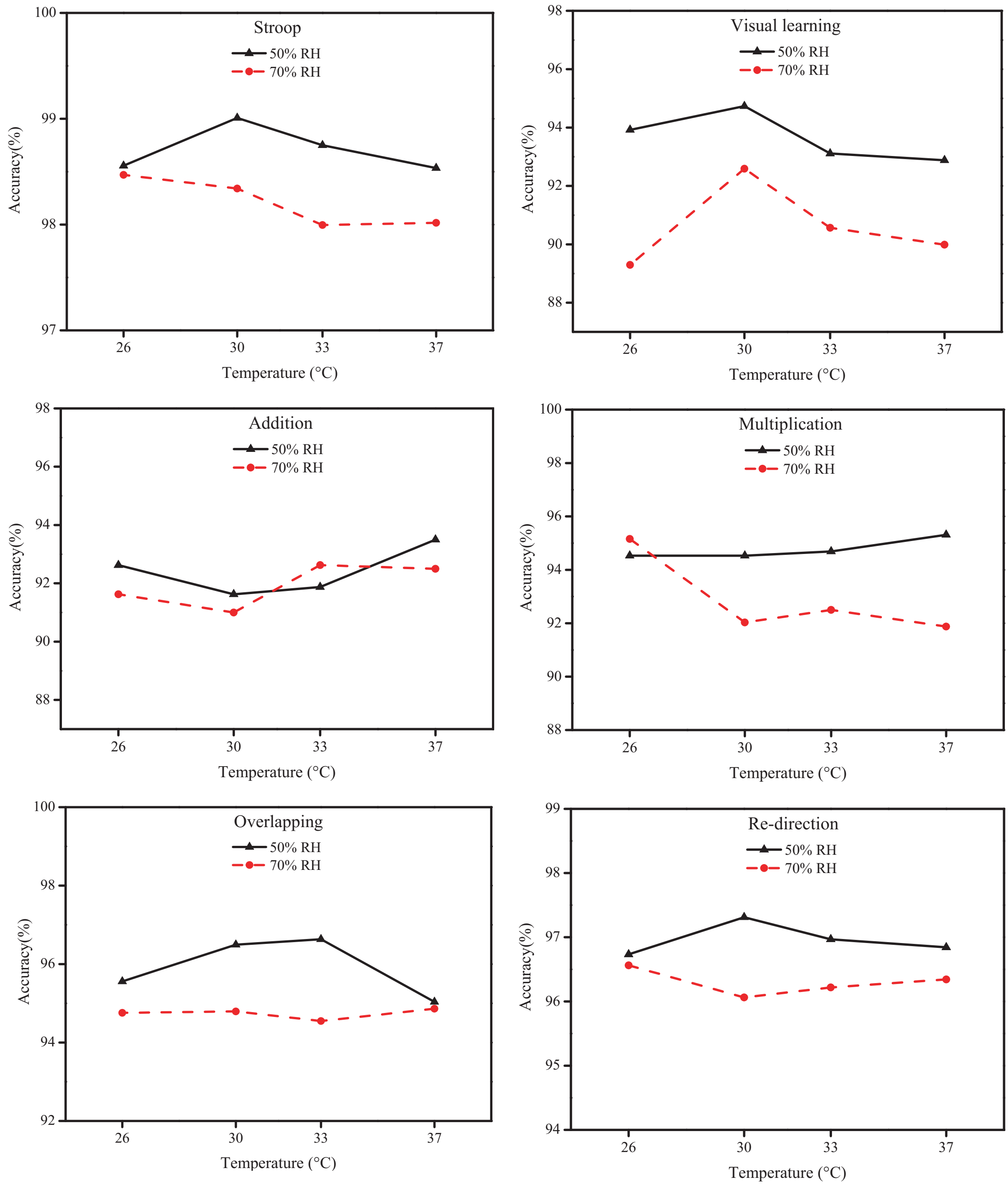


Fig. 6 Accuracy at which different neurobehavioral tests were performed at a different temperature and relative humidity levels

thinking. It was also seen that the performance of neurobehavioral tests was lower at higher relative humidity. This may suggest that EEG is a marker of effects on cognitive performance. This postulation is in agreement with the results of temperature on performance and EEG: temperature did not have any effect on the performance of neurobehavioral tests and nearly no effects were seen of temperature on EEG except at the highest temperature of 37 °C when RH was 70%. Even though present results suggest the link between EEG and cognitive performance, a similar link seems not to exist between EEG, thermal sensation, and thermal acceptability. No effect of increased relative humidity was observed on the thermal sensation and acceptability of thermal environment, which is consistent with previous research [59, 60]. This is somewhat inconsistent with the results of a few studies that examined whether EEG is changing in response to elevated temperatures. For example, Yao et al. [9] suggested that EEG signals may be related to thermal comfort, and may provide useful information for thermal comfort evaluation. Lan et al.

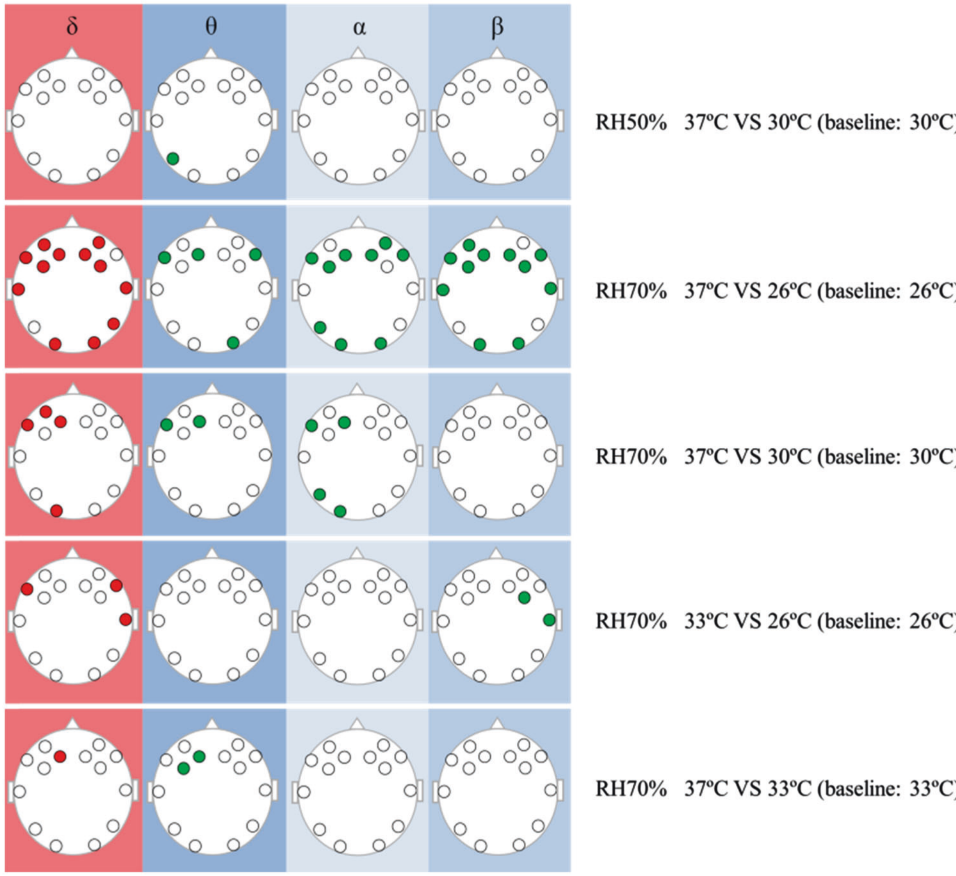


Fig. 7 The changes in the response of different EEG bands with changing temperature at RH of either 50 or 70%

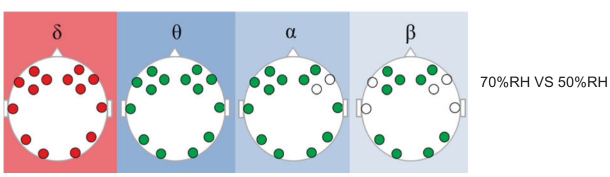


Fig. 8 The changes in the response of different EEG bands when relative humidity was increased from 50 to 70% independently of temperature level

[61] show that the relative power of the δ-band increases during a neutral thermal sensation. More research is needed to examine further the link between EEG and performance and whether EEG can be used as a marker of reduced performance, particularly whether it is sufficient to measure only one waveband to identify such effect.

It may be surprising that performance was not affected by increased temperature even though the temperature increased to as high level as 37 °C. Previous studies [10, 11, 62, 63] showed consistently that increasing temperature would result in reduced performance. Seppanen et al. [64] show that temperature above 23–24 °C will gradually reduce performance in moderate climate, i.e., people not adapted to tropical conditions and Lan et al. [65] showed that thermal discomfort due to warmth also reduce performance. Increased temperatures significantly changed thermal sensation and reduced acceptability of thermal environment but there was no effect on cognitive performance. No obvious explanation of this finding can be provided. One reason could be the lack of sensitivity of the used performance tests to detect effects but it must be rejected because other studies showed that they could detect the effect of elevated temperature on cognitive performance [42, 45, 46]. Another explanation could be that the subjects were highly motivated and performed the tests as good as they could. It should, however, be mentioned that no bonus was proposed to the subjects for their performance of neurobehavioral tests. A most likely explanation for the lack of effect is that the tests were performed early during exposure. Future experiments should address these issues especially looking at the impact of acclimatization and adaptation. The recent study of Porras-Salazar et al. [66] shows that pupils' acclimated to higher temperature perform school tasks optimally at a higher temperature than pupils from temperate climates.

In a recent study [8], the EEG signals at ambient conditions of 25 and 32 °C were compared, and no significant differences were found in θ-band, α-band, and β-band; only significant higher δ-band relative power was found in two channels at the ambient temperature of 32 °C. This is consistent with the present results showing that the effects on EEG occurred only at the highest temperature. In another study [67], the EEG signals were recorded at ambient conditions of 22 and 25 °C. Machine learning was adopted and the simple k-means clustering method was used to classify EEG data according to different temperature conditions. The study was not able to find any effect of temperature on EEG signals.

Motivation could be one of the reasons why the performance of neurobehavioral tests was different at two levels of relative humidity examined in the present experiments. It is worth recalling that the present study was performed in two experiments, first with relative humidity at 70% and one month later with a relative humidity of 50%. Subjects could be less motivated by the former though it is unlikely as it was performed first, so it is likely that subjects were more motivated at the onset of the study. Their motivation could be reduced by unfavorable conditions such as a relative humidity of 70%, being quite unpleasant especially at high temperatures, but it is not clearly demonstrated by the subjective ratings of thermal environment, even though humid environments are expected to produce greater thermal stress by reducing heat loss from evaporation [68]. The effect of RH may also reflect gradual learning and adaptation to experimental conditions. We are not able to provide the answer to why RH affects performance. However, the results are consistent with the work of Trezza et al. [69] who showed that exposure to relative humidity higher than 57.8% reduces cognitive performance.

The high-humidity environment is not conducive to sweat evaporation. This may increase the core temperature resulting in increased pulmonary ventilation and reduced cerebral blood flow. The latter can cause insufficient delivery of matrix to the brain and excretion of heat from the brain [70]. Figure 9 shows the results of measurements of eardrum temperature. It shows that core temperature increased with increased temperature in the chamber and that high relative humidity exacerbated this effect, particularly at 37 °C. This result may suggest thermal stress at 37 °C and relative humidity of 70% at which the effect on EEG was highest.

The experiments with two different relative humidity levels were run in two seasons. Consequently, it can be anticipated that the seasonal differences in thermal responses could contribute to the observed changes in EEG responses. However, present results cannot be used to examine whether this was the case because EEG signals were not measured under the same conditions in both seasons.

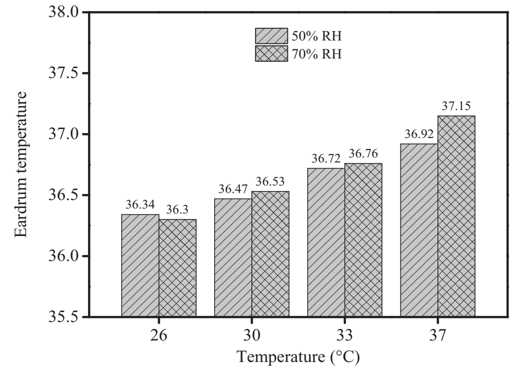


Fig. 9 Measured eardrum temperature of subjects at different temperature and relative humidity

One reason why the performance of neurobehavioral tasks was higher could be the gradual improvement of performance with the number of times the test is made, so-called learning [71]. The relative humidity of 50% was examined after four exposures to temperatures at a relative humidity of 70%. Although subjects performed the tests 10 times prior to the beginning of experiments, the learning effect cannot be rejected. To examine the existence of this effect the performance of the tests was plotted consecutively following the order at which the tests were performed independently of conditions in the chamber. Tables A and B in Appendix 6 in the supplementary material present the results of this exercise, which show that even though the tests were performed many times for some of them the learning effect still existed, in particular for the overlapping test. The existence of this effect may partially explain the effects of relative humidity on performance but does not explain the link between EEG and performance. EEG signal was examined for the tests for which learning effect was observed and no significant differences could be detected. This is inconsistent with what has been discussed earlier and puts into question the link between EEG and performance. Lack of this relationship could be because the effect on performance (learning) was small and could not be detected by EEG, but the present data are insufficient to examine this further. It is therefore important that more studies be carried out on the link between EEG and cognitive performance, especially with a focus on the effects of parameters defining the quality of indoor environments such as temperature, air quality, noise, and light [72].

EEG signals changed significantly at the temperature of 37 °C when relative humidity was 70%. At the same time, the subjects did not perform cognitive tests significantly differently at this condition. Assuming that EEG is a marker of cognitive performance, this result may suggest that EEG is more sensitive to detect the potential effects on cognitive performance than the cognitive tests used in present experiments. However, there are also other alternative interpretations of these results. They may simply suggest that the changes in EEG signals show that some physiological processes are taking place because of changing thermal conditions but the magnitude of these changes is too small to produce measurable effects on cognitive performance. These results may also suggest that there is no association between changes in EEG signals and cognitive performance. Present results cannot be used to demonstrate which interpretation is correct. More research is therefore needed to examine whether the changes in EEG signals can be used as a marker of reduced cognitive performance.

The relative power of δ-band (primarily representing sleep) increased significantly with increasing temperature at relative humidity of 70%, while at the same time the relative power of β-band (primarily representing active thinking) decreased significantly. This result may suggest that high humidity and high temperature increase sleepiness and increase difficulty to think clearly. The subjects rated their level of sleepiness, alertness and whether it was difficult for them to concentrate (see Fan et al. [31] and Appendix 2 for details). Their ratings of sleepiness did not change at different levels of relative humidity but they suggest that they could be less alert at higher humidity (Appendix 2). Their ratings indicate additionally that it was more difficult for them to concentrate at high relative humidity (Appendix 2). These results agree to some extent with EEG measurements, though it should also be noted that the relative power of θ-band (primarily representing drowsiness) decreased, which is inconsistent with the increase in relative power of δ-band (primarily representing sleep).

The limitation of the present study was that EEG was recorded only for 30 min and repetitions were made at the temperature conditions along the course of experiments. It was not possible to examine whether the EEG signal changed when the specific tests were performed. Another limitation was the restriction on randomization of relative humidity, which did not allow to examine interactions. Neurobehavioral tests were used and not the tests that are more close to the work performed in offices. This limits the generalization of the study results. Finally, young healthy students were used. It would be interesting to observe whether similar results could be observed for different age groups and for people with disabilities or atopy, as well as people not acclimatized to high temperature.

Conclusion

Increased relative humidity and increased temperature at high relative humidity caused measurable changes in EEG signals. These changes did not match the changes in thermal sensation or acceptability of the indoor environment. The changes were consistent with changes in the performance of neurobehavioral tests examining cognitive skills. However, gradual improvement of performance of these tests along the course of experiments independent of conditions could not be matched with the changes in EEG. These two results are inconsistent. Validity and usefulness of EEG for examining the effects of the indoor environment on human cognitive performance must therefore be examined further in future studies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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