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Investigating the effect of indoor thermal environment on occupants' mental workload and task performance using electroencephalogram

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ABSTRACT

Workers' performance in indoor offices can be greatly affected by the thermal condition of the environment. However, this effect can be difficult to quantify, especially when the thermal stress is a moderate increase or decrease in temperature and the work productivity cannot be directly measured. Subjects' high motivation to perform well under experimental conditions also causes difficulties in comparing their performance in different thermal environments. In order to overcome these limitations, this paper proposes a method to investigate the effect of the indoor thermal conditions on occupants' performance by studying occupants' mental workload measured by the electroencephalography (EEG) when they perform standardized cognitive tasks. An experiment integrating EEG mental workload measurement and cognitive tasks was implemented on 15 subjects. EEG data were collected while subjects were performing four cognitive tasks on computers. Based on previous studies, we propose a mental workload index calculated from the frontal theta and parietal alpha frequency band power. Within-subject comparisons were performed to investigate whether subjects' mental workload is statistically different under three different thermal environments, representing thermal sensations of slightly cool, neutral, and slightly warm. The results show that the effect of thermal environment varies across different individuals. By comparing the mental workload index among different thermal environments, we found that the slightly warm environment resulted in a relatively higher mental workload than the other two environments to achieve the same performance. The study provides promising insights into how the thermal environment influences occupants' performance by affecting their mental workload from the neurophysiological perspective.

1. Introduction

According to a survey involving more than 10,000 participants, people in the U.S. and Canada spent an average of 90% of their time indoors during the summer season and 96–98% during the winter season [1]. Therefore, the indoor environment of a building plays an important role in individuals' well-being and social development. At the same time, buildings are the largest energy-consuming sector in the U.S that use up about 39% of the total energy generated, of which over 80% is consumed during the occupancy phase [2]. Heating and cooling account for more than 60% of total energy requirements in residential buildings and approximately 50% in commercial buildings to ensure occupants' thermal well-being [3]. In spite of the high energy needed to control buildings' thermal environment, studies found that occupants, in general, are not satisfied with the indoor thermal environment, which leads to low workers' job satisfaction and results in an impact on their job performance [4,5].

Thermal comfort is one of the most important factors of indoor environmental quality (IEQ) that significantly affects occupants' satisfaction with the building environment and influences their health and well-being [6–9]. An undesirable thermal environment may lead to sick building syndrome symptoms such as eye, nose and throat irritation [10,11]. It also affects occupants' performance and productivity since difficulties in concentrating, clear thinking, and decreased self-estimated performance have been reported in the literature [10,12,13].

Previously, researchers investigated how different IEQ factors including lighting [14], noise [10,15], indoor air quality [16,17] and thermal comfort [10,18,19] affect occupants' performance. Improving workplace indoor environment is considered an important requirement to achieve higher worker comfort and well-being [12,20,21]. Moreover, it was shown that the high costs of implementing such measures are offset by the improved worker mental and physical health (e.g. reduced absenteeism) and productivity [22,23]. Controlling office room thermal condition through the heating, ventilation and air conditioning (HVAC) system by adjusting thermostat set points and humidifiers is one of the simplest ways to achieve an optimal workplace environment [5,24].

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Previous studies mainly focused on measuring the effect of thermal environment on subjects' task performance, using metrics such as work productivity and performance test results [18,25,26]. However, sometimes these methods do not work well because the effect of thermal environment is not directly reflected on the subjects' task performance [27]. Lan et al. (2009) [18] studied the neurobehavioral effect of room temperature on subjects using psychometric tests and found that factors such as subjects' motivation to perform well would offset the thermal effect on task performance [18]. There are some changes in subjects' mental and physiological states, such as stress level, heart rate variability, blood pressure and brain activity that could not be easily detected through measurements of the task performance alone [19,28–30].

To address the difficulties in directly measuring subjects' task performance, we propose to study how subjects' performance was affected by evaluating their mental workload. Mental workload is defined as "the mental resources devoted to the tasks of an individual" [31]. Developing a method to understand the effect of workplace thermal environments on workers' mental workload could provide us with insights into managing workplace temperature in order to achieve the highest worker performance and well-being.

Thus, the objectives of this paper are to examine (1) whether the change of an individual's mental workload due to the variations of thermal environments can be effectively detected; (2) how different thermal environments affect occupants' mental workload when performing same cognitive tasks; (3) how is occupants' mental workload related to their cognitive task performance under different thermal conditions.

To achieve this, the mental workload was measured using a low-cost, wireless electroencephalography (EEG) headset. EEG and task performance data were collected while the subjects performed four cognitive tasks characterizing typical cognitive functions under three different thermal conditions, slightly warm, neutral and slightly cool, derived from Fanger's Predicted Mean Vote (PMV) model [32]. A mental workload index was calculated using the relative power of the frontal theta and parietal alpha frequency band and compared by performing statistical analysis. The study also investigated the relationship between the mental workload index and occupants' cognitive task performance.

This paper is organized to first present a detailed review of existing related methods on studying the effect of indoor environments on occupants' performance and the main limitations of these studies. Then, we discuss in detail how EEG and the measurement of mental workload can fill the gap of the existing studies and introduce the methodology we propose to overcome existing limitations. Finally, results from the experiments are analyzed and discussed in detail, followed by the conclusions of this study.

2. Background

A significant amount of literature investigated how the workplace environment affects office workers' performance using various methods. In this section, we present a review of the three most-commonly-used methods and their limitations. First, the authors reviewed the subjective approaches to measure the performance of office workers. In these methods, the workers are asked to subjectively rate their self-perceived performance over a specific period of time. The second category consists of studies that assess performance by quantifying office workers' productivity in real office environments. The third category evaluates office workers' performance under different indoor environmental conditions based on the results of performance tests simulating or representing office work. Finally, the method we propose is introduced to bridge the research gaps in previous studies.

2.1. Subjective performance assessment

Self-assessment is one of the widely-used approaches to measure occupants' performance in office environments. McCartney and Humpreys (2002) proposed the Perceived Productivity Vote to assess how occupants' performance is affected by ambient environment conditions using a 5-point scale, ranging from "much higher than normal" to "much lower than normal" [13]. Akimoto et al. (2010) evaluated subjects' performance by examining their self-perceived mental workload and fatigue symptoms including "drowsiness and dullness", "difficulty in concentration" and "projection of physical disintegration" through questionnaires [12]. Tanabe et al. (2015) acquired occupants' self-assessment on their performance under specific indoor environmental conditions as a percentage of their performance in an optimum indoor environment, which is the most comfortable environment the subjects could imagine [20].

The main benefit of the subjective performance assessment approach is that it is convenient to implement and is independent of the type of task. The self-assessment results are direct and easy to be compared. However, self-perceived performance assessments are highly biased and subjective [13]. Although the same scales and even descriptions are specified in the questionnaires, different people can have a quite different understanding of what is being asked of them when they conduct the assessment. Even for the same subjects, it is difficult to control the scale because the responses are liable to be affected by the emotional condition of subjects [33]. In addition, occupants' subjective sensation of the environment and comfort level also affect their perception of their own performance. For example, subjects' ratings of their performance have been shown to be poorly correlated with the actual air temperature, but strongly correlated with their thermal satisfaction level [13,20]. It is also shown by previous studies that humans are not good at identifying the declination of their vigilance [34] and they may neglect or may not be able to perceive some minor effects of the environment on their performance. As a result, the subjective assessment has very limited value in evaluating the actual performance of occupants under different indoor environmental conditions.

2.2. On field productivity performance assessment

Another method to evaluate occupants' performance is to directly measure their productivity in real work conditions. However, only a limited number of studies using this method can be found in office settings, of which most of the existing studies looked at the effect of IEQ on the performance of workers in call centers. Federspiel et al. (2002) compared the talk time and wrap-up time of registered nurses working in a call center recorded by an automated call distribution system in the temperature ranging from 21 °C to 26 °C and found the nurses worked slower under warmer conditions [35]. Wargocki et al. (2004) evaluated the effect of indoor air quality on call center operators' performance by measuring their average talk time in a 30-min period and discovered a positive correlation between workers' performance and the air supply rate [36]. In another study on the effect of room temperature, the performance of call center workers was measured using the number of telephone communications divided by the active work time monitored by a computerized system, and a declined productivity was observed with increased temperature [37].

In order to directly measure occupants' performance in the field or the office, the work output should be clearly measurable. For instance, Kekäläinen et al. (2010) used the number of receipts handled as an indicator of salary calculation performance, and the number of vouchers handled as an indicator of concerned payment traffic [38]. However, unlike industrial work, few types of office work are repetitive with measurable output that could be technically monitored as in the call center scenarios. Nowadays, office work is becoming more and more complicated and involves a variety of different tasks and skills, such as management, communication, and analyzation. Thus, it is impractical to directly and accurately assess office workers' performance through their observed productivity in the workplace.

2.3. Performance assessment through standardized tests

The most common way to measure the performance of office workers is by using standardized performance tests that represent the typical activities of office work as a simulation in a laboratory environment. For example, Allen et al. (2016) used the Strategic Management Simulation software tool to assess the higher-order decision-making performance of management-level office workers [16]. However, developing this type of tools requires considerable expertise and money in order to scientifically simulate office work. Therefore, the availability of these tools is highly limited. It also requires a considerable effort for the subjects to learn how to use the simulation.

Some studies conducted several performance tests to evaluate different cognitive functions required to perform office work. For example, Lan et al. (2009) [18] proposed a neurobehavioral approach to evaluate office workers' performance under different thermal environments where four cognitive functions, including perception, learning, memory, and thinking, and executive functions are measured. A neurobehavioral test battery composed of nine representative psychometric tests was used to observe the direct effect of different room temperatures on occupant performance [18]. It was found that occupants' motivation has a higher priority to affect their performance than the adverse environment.

Some tests commonly used to evaluate office workers' performance in research studies include number calculation, memory, reading, and reaction [18,19,25,39]. Text typing, as one of the most common activities of modern office work, was also considered by several researchers [20,21,25]. The speed at which the subjects perform the tests and the accuracy of the test results were usually used as indicators of performance.

However, take room temperature as an example, significant effects of indoor air temperature on the results of performance tests have been observed by some studies [19,20,38,40], while no significant differences have been found by others [18,41,42]. As a result, a consistent conclusion of how occupants' performance is influenced by the office thermal environment could not be reached. One of the reasons is that the performance declines under adverse thermal conditions could be balanced out by the higher motivation and stress to perform well [43].

Another limitation of this method is that the experiments, or performance tests, have relatively short durations compared to the real office settings.

In most existing studies, the duration of a single performance test usually ranges between 5 and 20 min. Although in some studies the subjects were asked to stay for all day (e.g. 8 h) in a specific experimental environment, they were doing their own work or reading books most of the time to adapt to the experiment environment. The total duration of performing a task to measure their performance under a certain environmental condition typically ranged from 30 min to 2 h. During this short period of time, occupants are able to maintain their performance at a high level even if the environmental condition is not favorable. However, this is not necessarily the case in real office environments where occupants spend about 8 h per day performing their routine work. The long working time leads to a reduced motivation of office workers to maintain high performance at all times, especially under adverse environmental conditions [18].

Furthermore, the experimental settings adopted by these studies can also influence the result of the study. Reduction on occupants' performance was found when room temperature considerably deviated from the preferable value [21,39,40]. However, in the office environment, the room temperature is usually set within a moderate range such that no significant influence on performance test results was observed because performance can be maintained under moderate heat or cold stress [44–46].

In summary, the main limitation of performance assessment relying on the performance test data is that the adverse effect of uncomfortable thermal environment on subjects' performance test results is generally offset by subjects' motivation and ability to maintain their performance, especially considering the moderate heat or cold stress and the short duration in the experimental conditions. As a consequence, it could not accurately reflect workers' performance in actual office environments.

2.4. Objectives of the proposed approach

Previously, researchers found that when the type of performance task is different, room temperature has different effects on occupants' test results. Subjects' performance on tasks that more heavily rely on cognitive functions (e.g. working memory, reasoning) are more vulnerable to changes in room temperature [25,44]. For example, occupants' performance on mental arithmetic is found to be significantly affected by temperature. However, little effect of temperature was observed when occupants doing calculations with calculators and in the text typing task that do not require many cognitive activities [25]. Since different types of tasks are dominated by different brain cortical regions, it indicates that the variation on performance might be caused by the effect of thermal environment on neurophysiological activities [47].

One of the neurophysiological responses related to people's work performance is the mental workload. It indicates the amount of mental resource required to perform a set of concurrent tasks [48]. It describes the subject's personal effort and experience and indicates "an overall efficiency of human performance" when he/she performs tasks under specific conditions [28]. This demand is not only related to the characteristics of specific tasks but also depends on the individual who performs the tasks [49]. Changes in mental workload would ultimately cause changes in human behavior [28]. Sustained high mental workload will cause mental fatigue on subjects and bring about higher error rates, decreasing efficiency and alertness, and effort disinclination [50,51]. In the long run, it would result in decreasing performance and detrimental health effects on occupants [29,52]. Therefore, we propose to understand the effect of office thermal environments on occupants' performance through their mental workload.

3. Research methodology

In this study, a comprehensive framework is developed to study the effect of thermal environment on occupants' performance by first evaluating how thermal environment impact occupants' mental workload, then investigating how mental workload relates to occupants' task performance, as shown in Fig. 1. The temperature setpoints of the indoor environment are based on the PMV model, representing occupants' thermal sensation of slightly cool (21.7 °C/71.1 °F), neutral (25.2 °C/77.4 °F) and slightly warm (28.6 °C/83.5 °F). Under these three setpoints, the relative humidity (RH) was maintained at about 22–24%. The experiment settings will be discussed in detail in Section 3.3.2. Four cognitive tasks including number addition [25], forward digit span [53], choice reaction [54,55], and visual search [56] were selected to represent different cognitive functions. The subjects' mental workload was determined using a low-cost wireless EEG headset that the subject wore while they performed the cognitive tasks to understand how thermal environment affect occupants' performance in depth. The remaining part of this section first introduces the EEG and how it contributed to the objective of the study. Next, the experiment conducted is explained in detail and the methods for data preprocessing and analysis are discussed.

3.1. Electroencephalography (EEG)

Human physiological responses have been shown to vary with the ambient environmental temperature [57,58]. Therefore, the responses of various physiological factors in different thermal environments have

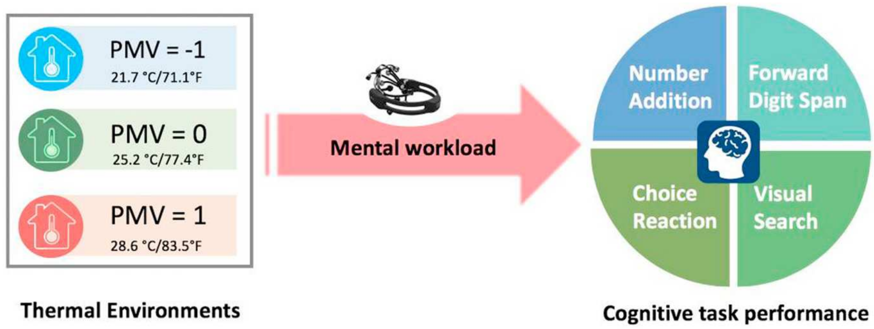

Fig. 1. Framework for studying the effect of thermal environment on mental workload and cognitive task performance.

been investigated by researchers. Several researchers studied the effects of temperature on heart rates [57], facial skin temperature [58], and respiratory rate [42]. However, these measurements are not sensitive enough to reflect the individuals' cognitive status because their responses to subjects' cognitive status are slow and weak compared to brain waves. Other peripheral physiological factors such as blink rate and duration [59] and wrist skin temperature [12] have limited accuracy in reflecting individuals' cognitive states. Some techniques such as positron emission tomography (PET), Magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) are able to detect subjects' central nervous activity directly but require cumbersome and expensive equipment and severely restrict subjects' activity, and thus impractical to be used in an ordinary experiment.

In this study, the authors propose to use EEG to detect the mental workload of occupants under different thermal environmental conditions. EEG is a noninvasive technique to monitor and record the electrical activity of the brain, typically through electrodes placed on the scalp surface [60,61]. When the neurons in the brain are activated, there is a voltage change on the cell membrane. The synchronization voltage change from tens of thousands of neurons can collectively generate an electric potential which could be detected by the electrodes. By directly capturing the activity of the central nervous system, EEG can accurately reflect brain neural activities and subjects' cognitive states [62].

Compared to other physiological responses, several characteristics of EEG make it a good candidate tool for our study [63]. First, it has a high time resolution (> 128 Hz) so that cognitive processes can be captured instantaneously. Second, it is portable, inexpensive and light in weight. Most importantly, EEG can directly monitor cognitive brain activities and can capture the slight variations in cognitive states which would otherwise be too subtle to be reflected from subjects' behavioral responses or other measurements [64]. Recently, the emergence of several low-cost EEG headsets makes it even more accessible to be used in research. In our study, we used a low-cost EEG headset (Emotiv EPOC+) that includes 14 channels and allows for fast setup without using gels or pastes. It can also record brain activities with reasonable quality and upload the data to ordinary PCs, Macs and smartphones wirelessly in real-time [65].

Several studies have explored using the EEG to investigate the effect of temperature on occupants. Yao et al. (2009) studied the global relative EEG power of different frequency bands on subjects' static status under different thermal conditions using a bipolar EEG while they are lying down with their eyes closed [57]. The study found that EEG could reflect subjects' thermal comfort sensation and is promising to provide a solution to some intractable problems in the field of thermal comfort. Lan et al. (2010) used EEG to explore how office temperature affects occupants' performance; however, the EEG was only recorded for three selected subjects after they finished their psychometric performance tests but not in real-time while they were performing cognitive activities [66]. Choi et al. (2019) compared how occupants' attention ability changed over time while they are studying in different room temperature. However, the difficulty of the task performed by subjects under each thermal condition was not controlled [67]. Hocking et al. (2001) evaluated soldiers' cognitive performance under severe heat stress which is unusual in building indoor environments [19]. The elaborate EEG system used in this study provides high-quality signals and allows for in-depth data analysis. However, this device is cost prohibitive and time-consuming to set up, which significantly limits its applications in other research studies and practical settings.

To address the limitations mentioned above, this study distinguishes from prior studies in three aspects: (1) the temperature range in our experiment was set to be moderate (21.7°C-28.6 °C/71.1°F-83.5 °F), which represents slightly cool (PMV = −1), neutral (PMV = 0), and slightly warm (PMV = 1) conditions that are typical in office buildings; (2) the EEG signal was captured at the same time while subjects were performing cognitive tasks, which allows us to understand subjects' mental workload in different tasks and how it relates to the task performance; and (3) the cognitive tasks and their difficulty levels were controlled to be the same for all subjects. Each subject was required to perform the tasks in the same order under the three thermal conditions.

The frequency band power data was achieved from the bundled software of the EEG device calculated at a frequency of 8 Hz (i.e. for each 125 ms period). Hanning window was used for the Fast Fourier Transform [68]. Since the delta frequency band (1–4 Hz) is only associated with deep non-REM sleep and frequencies higher than 45 Hz is still not clear to researchers [69], frequencies lower than 4 Hz or higher than 45 Hz were excluded from analysis. The band power data collected each day were sliced into different segments with each segment only containing the data for one type of task at one difficulty level.

3.2. Experimental setup

A three-day experiment was designed to use EEG to record brain electrical signals while subjects performed cognitive performance tests. Subjects were also asked about their self-perceived performance and mental workload ratings. The experiment was conducted in a research office with a desktop personal computer at the University of Michigan during the heating season from November 2018 to January 2019 (see Fig. 2). The office is in the basement and does not have windows or other sources of daylight or natural ventilation. The air quality, ventilation, and lighting conditions were controlled to be the same during the experiments. Two COZIR temperature/humidity sensors (humidity accuracy: ± 5%; temperature accuracy ± 1%) were used to continuously measure the ambient conditions of the subject in the testbed office. According to the ASHRAE standards 55, the sensors are placed 0.6 m above the floor level [70]. The temperature is controlled by the air-conditioning system linked to a thermostat in the testbed office, which allows the temperature to be freely changed in the range from 20 °C to 30 °C. The experiment protocol was approved by the Institutional Review Board at the University of Michigan.

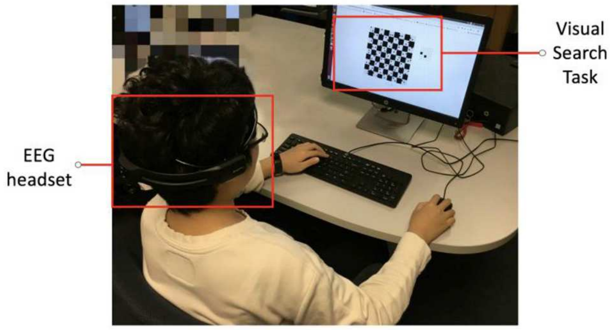

Fig. 2. Experiment setup.

3.2.1. Subjects

Fifteen subjects participated in and completed the experiment. All subjects were graduate students at the University of Michigan aged between 22 and 33, who were healthy and well-acquainted with computer use. Each subject received a gift card as the compensation after they completed the experiment. In order to get the clean EEG data, subjects were required to comply with the following requirements before and during the experiment: (1) wash and dry their hair without hair care products (conditioner, hairspray, etc.) before coming to experiment; (2) try to sleep and wake up at the same time each day and ensure a good night's sleep during the three-day experiment; and (3) do not take alcohol, coffee, tobacco, or other drinks that can cause excitement or drowsiness during the three-day experiment period. We also asked the subjects to wear the same clothes (long-sleeved sweater, long trousers) and shoes throughout the whole experiment period.

At the start of the experiment, we assigned each subject a unique ID number as an identifier for data reference. No identifiable information was used for data storage and analysis. The subjects were asked to treat the tasks seriously as they do in their daily work.

3.2.2. Cognitive tasks

Four computer-based cognitive tasks were selected to arouse subjects' functions on thinking, working memory, perception, and reaction. Tests results were recorded and subjects were also asked to evaluate their performance. All tasks were developed using the Javascript language. The subjects were not allowed to take any notes or use a calculator during the tasks. A detail description of each task is presented below.

Task 1 - Number addition (thinking): In the number addition task, a column of randomly generated numbers was shown on the computer screen (Fig. 3(a)). The subjects were asked to add up all the numbers in

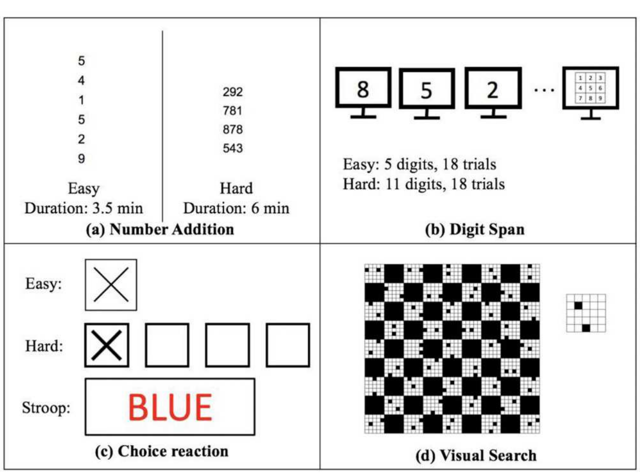

Fig. 3. Cognitive task interface.

the column mentally and then enter the results in a textbox given below using a keyboard [25]. After clicking the 'Continue" button, a new column of numbers would appear on the screen until the time ran out. The task was divided into two difficulty levels. In the easy level, there are six one-digit numbers in a column. In the hard level, there are four three-digit numbers in a column. The task starts with the easy level that lasts for 3.5 min followed by the hard level which lasts for 6 min. However, the EEG data of the first 0.5 min of the easy level task were removed to exclude the unstable factors when the subject just started a time-limited task. The number addition tasks require subjects' thinking functions such as computation and problem-solving skills. The number of correct answers subjects could get in a given time period was used to measure their task performance.

Task 2 - Forward Digit span (working memory): The forward digit span task was adapted from the Wechsler Adult Intelligence Scale (WAIS), which was a traditional test to measure subjects' verbal working memory and attention [53]. A sequence of digits appears on the screen for 800 ms one after another with a 200 ms gap time between every two digits (Fig. 3(b)). Once all the digits showed up and disappeared from the screen, subjects were asked to recall the digit sequence and input it through the number pad on the computer screen. There are two difficulty levels with 18 trials in this task. Subjects were asked to memorize five digits for one number sequence at the easy level and eleven digits for one number sequence at the hard level. We measured how many digit sequences the subjects can memorize correctly out of the 18 sequences given at each difficulty level and used it as the indicator of their task performance.

Task 3 - Choice reaction (reaction): The choice reaction task was divided into three sections, with 60 trials each (Fig. 3(c)). The first two sections were adapted from the Deary-Liewald task [54], while in the third section we used the Stroop task [55], which is one of the most famous psychological tests on choice reaction. The first section is a simple reaction task where the subjects need to press a single button on the keyboard as fast as possible whenever an X-shape stimulus appears in the center of the computer screen in a square box. In the second section, there were four boxes arranged as a horizontal line in the center of the screen. The subjects were asked to press the corresponding keys on the keyboard with the same alignment as the position of the square boxes, which are 'z', 'x', 'comma' and 'full-stop', as soon as the x-shape stimulus appears in the corresponding boxes. In the third section, a color name appeared in the center of the screen in different font colors one at a time. Subjects were requested to respond to the font color of the word regardless of its actual meaning by pressing the first letter of the font color on the keyboard. The choice reaction task requires subjects' ability to react correctly and quickly to the stimulus and ignore useless and interfering information. We quantified subjects' performance on this task by the average response time of the trials that they response correctly to the stimulus.

Task 4 - Visual Search (perception): The visual search task requires the subjects' visual perception ability to rapidly and accurately search for the target object. In our experiment, we revised the traditional visual search task from Goldstein et al. (1973) [56]. As shown in Fig. 3(d), on the left side of the computer screen, there is a 9 × 9 grid with 41 white squares segmented by 40 black squares. Each white square is a 5 × 5 grid with exactly two squares colored in black. A target white square was shown on the right of the screen and subjects were tasked to find out the location of the target from the 9 × 9 grid and type its coordinate in the textbox below. The task lasts for 9.5 min in total; however, the EEG data from the first 0.5 min were excluded to ensure the subjects were in a steady state. New trials would appear after the subjects clicked the "Continue" button and repeat until the time limit was reached. The number of correct answers subjects get in the given time was used as the indicator of their task performance.

According to the effort the tasks typically required and the feedback from the Beta experiment, we categorized them into two classes (see Table 1). Tests in Class A are more mental-effort-intensive, while tests

Table 1
Cognitive tasks categories.

Category	Mental Effort Demand	Task Type
Class A	Relatively high	Number addition Forward digit span
Class B	Relatively low	Choice reaction Visual search

in Class B are relatively easy. Before the experiment, the demos of each task were provided to eliminate subjects' learning effect during the experiment period. Subjects were requested to get enough practice to get familiar with the tasks before the experiment started.

3.2.3. Experiment protocol

In our experiment, the temperature settings were derived from Fanger's PMV model [32]. The PMV model is an international standard to evaluate the occupants' indoor thermal comfort based on the human body's thermal balance equation. It uses four environmental parameters including air temperature, mean radiant temperature, air velocity, and relative humidity, and two occupant-related parameters, including metabolic rate and cloth insulation, to predict occupants' thermal comfort level corresponding to a 7-point thermal sensation scale. Given that the temperature in an office environment is usually controlled in a moderate range, we set the thermal condition to be PMV = −1, PMV = 0, PMV = 1, which corresponds to slightly cool, neutral, and slightly warm on the thermal sensation scale, respectively. The thermal condition settings for each environmental condition is presented in Table 2.

In order to eliminate the effects caused by factors other than the thermal environment, such as sleep deprivation, we adopted several approaches from the literature that studied the thermal environment using EEG [19,66,67], and also from the literature that evaluated mental workload using EEG [29,65]. These approaches include: (1) Subjects were required to come to the experiment at the same time on three consecutive days to eliminate the circadian effects; (2) Subjects had to meet all the requirements stated in 3.3.1 to participate in the experiment and get enough practice on the cognitive tasks beforehand to eliminate the learning effect; and (3) Subjects were required to take the task seriously (i.e. pay full attention and try the best to get correct answer). In order to balance out the influence of the subjects' familiarity with the experiment, Latin Square Design was used to shuffle the order of different experimental conditions (i.e., thermal conditions) on each day for the subjects. The fifteen subjects were randomly divided into three groups (G1, G2, G3) and followed the experimental settings as shown in Table 3.

In each experimental condition, the subjects followed the procedures shown in Fig. 4. Before the experiment started, the subjects spent 30 min reading books or listening to music to adapt to the environment. On the first day, the instructions of the experiment were given during this period. In the next 15 min, the EEG headset was set up on the subject's scalp. The device was linked to the bundled software on a laptop computer through Bluetooth. The laptop was used to monitor the contact quality of each EEG channel which could be visualized through the software interface [71], as shown in Fig. 5. Each spot represents a channel, where green spot represents good contact quality, and orange and red spots indicate the channel is partially connected. If the spot is in grey, it means the channel has a poor connection. This same approach was used to continuously measure the contact quality as the subjects performed the tasks during the experiment. Only data from subjects with continuous good connection in all channels during the tasks were accepted for analysis. The authors also checked the subject's scalp status before and after each cognitive task section to ensure there is no sweating on the scalp that would affect the EEG data quality. After setting up the EEG device with good connectivity, the subjects performed their first cognitive task section. To prevent subjects from feeling overwhelmed or fatigue, we selected one task from Class A and one task from Class B and combined them into Cognitive tasks-1 (see Table 1). Cognitive tasks-2 was the combination of the other two tasks left. The task combination was randomly shuffled to counterbalance the effect of sequence on their performance among subjects; however, for each subject, the task combination and sequence remain the same on each day. Between the two cognitive task sessions, subjects had a 15-min rest with EEG headset removed from their scalps.

Table 3
Experimental settings for each group.

Group	Day 1	Day 2	Day 3
G1	PMV = −1	PMV = 0	PMV = 1
G2	PMV = 0	PMV = 1	PMV = −1
G3	PMV = 1	PMV = −1	PMV = 0

3.3. Data analysis

The frequencies of the EEG are categorized into 5 different frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–25 Hz) and gamma (> 25 Hz) [72]. As task demand increases, the theta band activity of frontal lobe increases significantly, while the alpha band activity of parietal lobe decreases [28,29,73]. The changes of the frontal theta and parietal alpha could be reflected by the relative power spectrum of the corresponding frequency bands detected by the channels in the specific regions [28]. Moreover, Holm et al. (2009) compared several indexes derived from EEG signal and indicated that the ratio of frontal theta and parietal alpha has a more accurate reflection of the mental workload [29].

For the EEG headset used in this study, there are two electrodes to monitor frontal lobe activity (F3, F4) and two electrodes to monitor parietal lobe activity (P7, P8). After slicing data into different segments according to the start and end time of each level of task, the relative power (RP) of a certain frequency band can be calculated using Eq. (1). The band power in the equation is the average power of the certain frequency band in a segment:

$$\text{Relative power (RP)} = \frac{\text{power of certain frequency band}}{\sum \textit{all frequency bands power}}$$

$$\text{Mental workload index} = \frac{\text{Average frontal theta power}}{\text{Average parietal alpha power}} = \frac{\text{F3 theta RP} + \text{F4 Theta RP}}{\text{P7 Alpha RP} + \text{P8 Alpha RP}} \quad (1)$$

A mental workload index was developed based on the study of Holm et al. (2009) by calculating the ratio of frontal theta power and parietal alpha power. Since there are two electrodes in each region on the EEG headset, we used the average value of the relative power from two electrodes to calculate the mental workload index, as shown in Eq. (2).

Table 2
Experiment environmental conditions.

PMV	Thermal Sensation	Air Temperature	Relative Humidity
PMV = −1	Slightly cool	21.7 °C ± 0.1 °C (71.1 °F ± 0.2 °F)	23% ± 1%
PMV = 0	Neutral	25.2 °C ± 0.1 °C (77.4 °F ± 0.2 °F)	23% ± 1%
PMV = 1	Slightly warm	28.6 °C ± 0.1 °C (83.5 °F ± 0.2 °F)	23% ± 1%

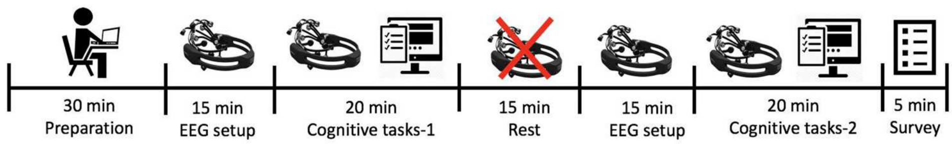

Fig. 4. Experiment procedure on each day.

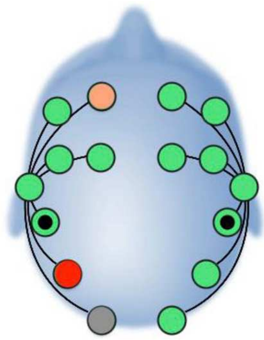

Fig. 5. Eeg headset contact quality interface.

A higher mental workload index indicates that the subject has higher mental workload while performing the tasks.

$$\text{Mental workload index} = \frac{\text{Average frontal theta power}}{\text{Average parietal alpha power}} = \frac{\text{F3 theta RP} + \text{F4 Theta RP}}{\text{P7 Alpha RP} + \text{P8 Alpha RP}} \quad (2)$$

By comparing the RP from the four electrodes and mental workload index at the easy and the hard task difficulty level, it was also found that the mental workload index could reflect the mental workload better. By comparing subjects' mental workload of the two task difficulty levels, we found the mental workload index, the ratio between average frontal theta band power and average parietal band power, is more accurate on reflecting mental workload than single electrodes. In 97 out of 108 cases, the mental workload index while subjects worked on the hard-level task is higher than that on the easy-level task. Therefore, the mental workload index was used for further analysis. Since the EEG pattern of different individuals could be very different and not comparable [74], the Wilcoxon signed-rank test was conducted to compare the within-subject differences between each pair of thermal environments (e.g., slightly warm vs. neutral).

4. Results

The data from 2 subjects were excluded from the analysis because of the poor electrode connectivity (shown in orange, red or grey color in the software, see Fig. 5) during part of the experiment [71]. One subject was also excluded due to sweating in the slightly warm (PMV = 1) environment. Sweat accumulated on the scalp has been suggested to influence the electrode impedance and consequently affect the EEG signal. As a result, the EEG signal from all the remaining 12 subjects had good quality on all channels during the tasks and was used for further analysis.

The timestamps when the first formal trial started and the subject submitted their answer for the last trial were recognized as the start and end time of each cognitive task, respectively. The EEG signal between the start and end time of each task was selected and used as the dataset for the task. In the following sections, the indexes of mental workload for all the datasets were analyzed and compared.

4.1. Comparing the effect of thermal environment on mental workload in specific tasks

As found by the previous studies, different individuals have different preferences for indoor thermal environments [6,75]. In order to investigate whether thermal environments have an impact on different individuals' mental workload even when they were performing same types of tasks, we compared the mental workload index of individuals for each type of task under three different thermal environments, as shown in Fig. 6. The colored boxes represent the value of mental workload index for each subject in different thermal environments. To avoid the confusion caused by the overlap of the boxes, a small horizontal bar was added on the right side of each box so that the comparison results could be visualized more clearly.

Even for the same type of task, thermal environments have different effects on each subject's mental workload. The change of room temperature causes the mental workload of some subjects to increase while results in the decline of some other subjects' mental workload. Take Fig. 6(h) for example, comparing to the neutral environment (PMV = 0), the slightly cool environment (PMV = −1) reduces the mental workload of Subject 3 and 4, while causes increase in the mental workload of Subject 11 and 12, showing individual differences in the effect of thermal environment on mental workload. In spite of the individual differences, the mental workload under the slightly warm (PMV = 1) condition was the highest among the three thermal conditions in 82 out of the 96 cases, suggesting a generally increased mental workload when the room temperature was higher. 23 out of 96 of the mental workload indexes are higher than 2.0, of which 21 are from the PMV = 1 condition, indicating performing tasks under slightly warm conditions can cause considerably high mental workload.

4.2. Comparing the effect of thermal environment on mental workload in specific individuals

As observed in Section 4.1, for each type of task, even though the slightly warm thermal environment generally resulted in higher mental workload than the slightly cool and neutral environment, no significant difference on the mental workload between the slightly cool and neutral environment was found for all tasks. Even the task type and its difficulty were the same, individual differences caused some subjects to have higher mental workload in the neutral environment than the slightly cool condition, and vice versa for others. In this section, the authors examined whether the mental workload changes in the same pattern across different types of tasks within each subject. Wilcoxon signed-rank test was used to compare the mental workload index in different thermal environments for each subject at the confidence level of 95% (Table 4).

For different subjects, the thermal conditions where we observed significant differences in mental workload turn out to be different. For some subjects, significant increases in mental workload could be found as the environment becomes warmer, such as Subject 8. The mental workload of Subject 8 increases significantly as the room temperature increases, although with exceptions between the slightly cool and neutral environments for easy level number addition and the neutral and slightly warm conditions for hard level choice reaction task. For Subject 7, the mental workload under the slightly warm condition was significantly higher than the slightly cool and neutral environments. However, the mental workload did not change significantly between the slightly cool and neutral environments. For some other subjects, the mental workload in the neutral environment was found to be significantly lower than the other two. For example, the mental workload of Subject 5 and Subject 11 reached the lowest point in the neutral conditions for most tasks, suggesting the neutral environment is

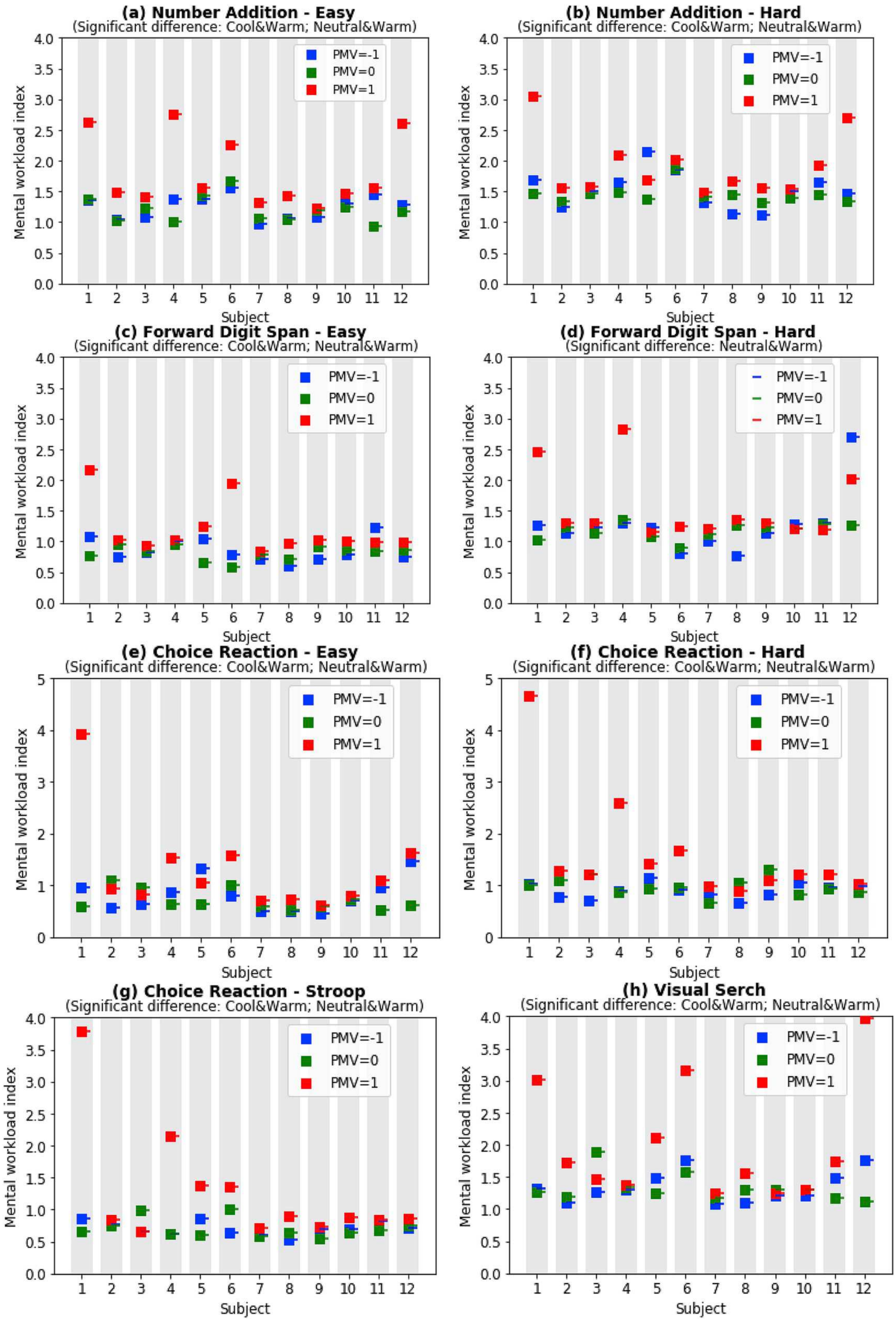

Fig. 6. Comparison of the mental workload of each type of cognitive task under the three thermal conditions.

potentially the best for their workplace.

Despite the fact that such trend and statistical differences in mental workload among three thermal environments could be found for most subjects, the changing pattern of mental workload for Subject 3 was not as clear as others. The reason could either be the inconsistency of the subject's mental status during part of the experiment or the fact that the subject's mental workload was affected by other factors more significant than the thermal environment. Future research is needed to study the reason for this phenomenon in depth, which was not included in the scope of this study.

Table 4
Comparison of mental workload of each individual under three thermal conditions.

Subject	Parameter	PMV = −1	PMV = 0	PMV = 1	Significant difference
1	Mean	1.198	1.024	3.212	PMV = −1 & PMV = 0;
	SD	0.247	0.308	0.794	PMV = −1 & PMV = 1;
					PMV = 0 & PMV = 1
2	Mean	0.924	1.088	1.272	PMV = −1 & PMV = 0;
	SD	0.220	0.171	0.296	PMV = −1 & PMV = 1
3	Mean	0.990	1.217	1.176	PMV = −1 & PMV = 1
	SD	0.306	0.316	0.310	
4	Mean	1.127	1.033	2.044	PMV = −1 & PMV = 1;
	SD	0.315	0.309	0.631	PMV = 0 & PMV = 1
5	Mean	1.326	0.994	1.450	PMV = −1 & PMV = 0;
	SD	0.360	0.318	0.315	PMV = 0 & PMV = 1
6	Mean	1.142	1.195	1.905	PMV = −1 & PMV = 1;
	SD	0.466	0.424	0.574	PMV = 0 & PMV = 1
7	Mean	0.876	0.924	1.066	PMV = −1 & PMV = 1;
	SD	0.250	0.289	0.271	PMV = 0 & PMV = 1
8	Mean	0.797	1.000	1.191	PMV = −1 & PMV = 0;
	SD	0.246	0.317	0.336	PMV = −1 & PMV = 1;
					PMV = 0 & PMV = 1
9	Mean	0.909	1.049	1.102	PMV = −1 & PMV = 1
	SD	0.252	0.304	0.289	
10	Mean	1.068	1.023	1.178	PMV = −1 & PMV = 1;
	SD	0.284	0.274	0.244	PMV = 0 & PMV = 1
11	Mean	1.234	0.976	1.321	PMV = −1 & PMV = 0;
	SD	0.274	0.291	0.358	PMV = 0 & PMV = 1
12	Mean	1.394	0.999	1.973	PMV = −1 & PMV = 0;
	SD	0.602	0.245	1.008	PMV = 0 & PMV = 1

4.3. The relationship between subjects' mental workload index and their cognitive task performance under different thermal conditions

In order to study how subjects' mental workload relates to their performance on cognitive tasks, we studied the ratio between subjects' cognitive task performance and their mental workload on corresponding tasks. The ratio reflects the amount of performance subjects achieved (i.e. get one more correct trial, reduce response time by a certain amount of time) per unit of mental workload, and thus a higher ratio indicates a higher efficiency for subjects' mental effort to be reflected on task performance. The results are shown in Fig. 7. The colored boxes in different color represent the performance/mental workload index ratio for each subject in different thermal environments. For the choice reaction task, we used the reciprocal of the average response time (s) to facilitate comparison and visualization.

For all types of tasks except the easy level forward digit span task, the performance/mental workload index ratio under the slightly warm condition is significantly lower than the neutral and the slightly cool conditions. For the easy level forward digit span task, the significant difference on the ratio was only found between the slightly warm and slightly cool environment. With an equal amount of mental workload exerted, less performance was achieved in the slightly warm environment, meaning subjects have to spend higher effort in the slightly warm environment to maintain their task performance.

5. Discussion

This study used the mental workload measured by the EEG to investigate how subjects' performance is affected by the thermal condition of their working environment. Compared to methods from previous studies that directly measured workers' actual productivity [35–37] or using the result of simulation tasks [16] or neurophysiological tests [18,25] to reflect subjects' performance of office work, the proposed approach provides more profound results by including the effect on the neurophysiological level. It also avoided the bias caused by the subjective assessment of their own performance [3,12,13]. By directly measuring the activity of the central nervous system, EEG signal has a higher sensitivity and a faster response to subjects' mental workload than peripheral measurements such as heart rate [57] and skin temperature [58]. The cognitive task could be changed to other customized tasks or actual office work, thus the proposed method provides more variability on the type of work being performed.

5.1. Mental workload index

A mental workload index developed and validated in Section 3.3, is used here for further analysis. Although the mental workload index could efficiently reflect the change of mental workload within each task type, it was not comparable among different individuals and different task types. The reason for that is the brain processes each type of task differently and calls different brain functions to deal with the task. This is why different changing patterns were found when the same subject performing different tasks. For example, as rated by subjects, the difficulty of the choice reaction task is lower than the other three tasks; however, the difference was not reflected by the mental workload index. Different from the other tasks that involve mainly mental process, the choice reaction task requires subjects' quick response by pressing corresponding keys as fast as possible on the keyboard. It will also call the subject's motor function to control the execution of muscle activity [60]. Therefore, we only performed comparisons within each task type and each individual. In future studies, the mental workload of different types of tasks could be measured using different indexes catering to the brain processes of performing those tasks.

5.2. The effect of thermal environment on mental workload

In Section 4.1 and 4.2, we compared different individuals' mental workload indexes under three thermal conditions for each type of task. The effect of thermal environment on each subject's mental workload was not the same. One reason is that the PMV model represents a general thermal sensation based on data collected from thousands of people. However, it does not necessarily ensure every subject to have the same feeling to the thermal environment [6]. When subjects finished their experiment each day, they were asked to take a survey to rate their thermal sensation during their experiment on that day. Take the slightly cool environment for example, while 9 out of 12 subjects

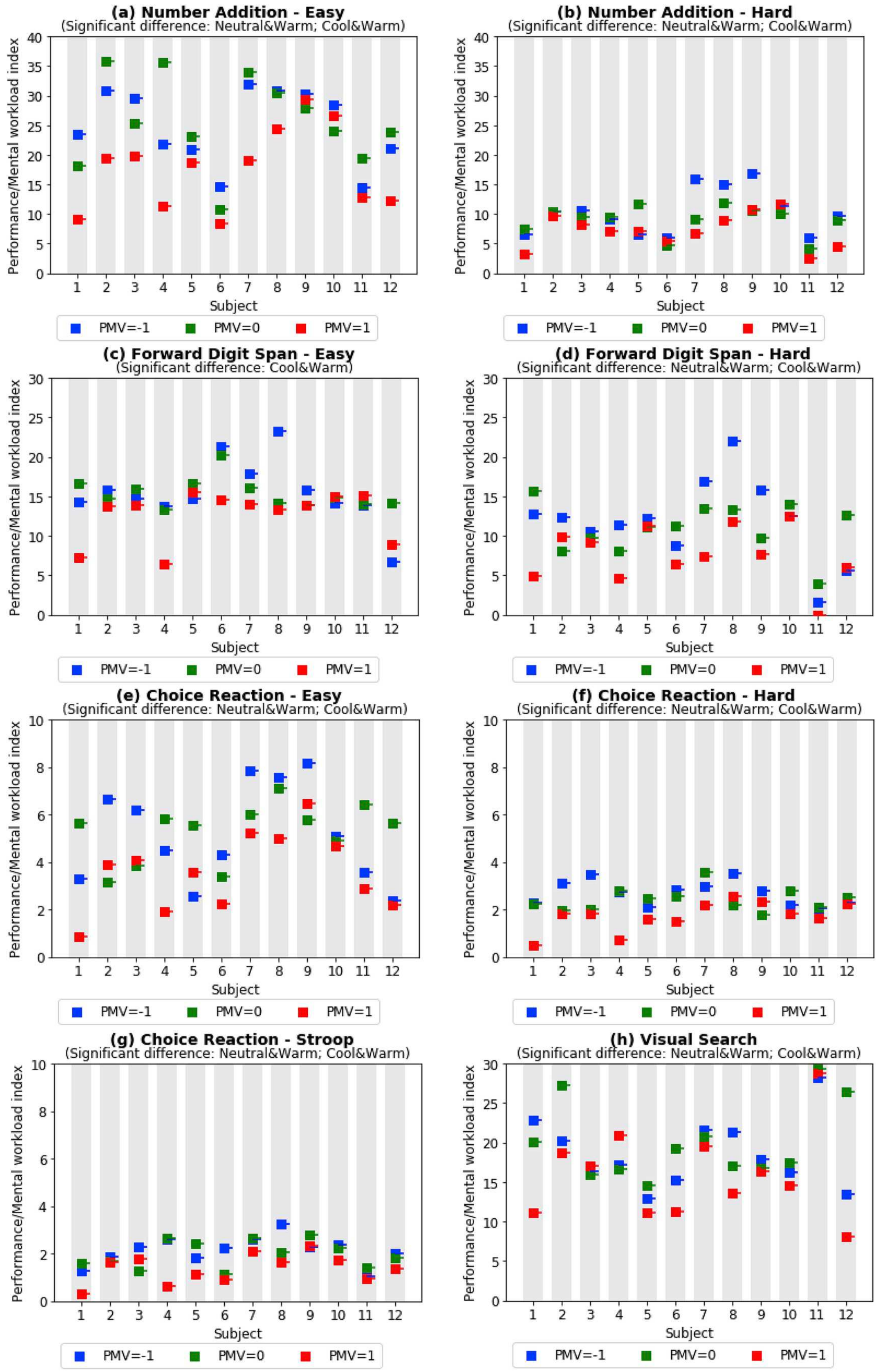

Fig. 7. Comparison of performance/mental workload ratio ($P < 0.05$).

Table 5
Comparison of task performance results.

Task	Statistics	PMV = −1	PMV = 0	PMV = 1	Differences ($p < 0.05$)
NA-Easy (correct number)	Mean	29.533	29.667	27.933	No
	SD	4.588	6.030	5.972	
NA-Hard (correct number)	Mean	15.267	13.733	13.000	PMV = −1& PMV = 1
	SD	3.275	3.660	3.425	
DS-Easy (correct number)	Mean	17.867	17.867	17.933	No
	SD	0.340	0.340	0.249	
DS-Hard (correct number)	Mean	11.733	10.667	9.533	PMV = − 1 & PMV = 1
	SD	6.016	5.249	5.175	
CR-Easy (response time (ms))	Mean	280.278	277.765	283.849	No
	SD	19.971	14.585	20.671	
CR-Hard (response time (ms))	Mean	433.741	444.952	452.519	No
	SD	27.084	27.907	44.208	
CR-Stroop (response time (ms))	Mean	719.590	784.256	787.110	PMV = −1 & PMV = 0; PMV = −1 & PMV = 1
	SD	143.832	127.758	154.016	
VS (correct number)	Mean	39.533	37.600	34.733	PMV = −1 & PMV = 1
	SD	8.898	7.998	10.292	

reported to feel slightly cool (PMV = −1), 2 subjects felt cold (PMV = −1) and 1 subject felt neutral (PMV = 0). In other words, although most subjects feel slightly cool under the PMV = −1 environment, some may feel neutral or cold. Another reason is that thermal sensation influences subjects' performance in different ways. Some people may feel soberer when they feel slightly cool and can solve problems better due to the arousal effect of the environment, while others are distracted by the coolness and could not firmly focus on their work [57,76]. The individual difference was further proved in Section 4.3 that for some subjects, the mental workload in the slightly cool environment was significantly lower than the neutral environment while vice versa for some others.

5.3. Mental workload and cognitive task performance

To investigate the relationship between subjects' mental workload index and their cognitive task performance, we first performed a within-subject comparison on subjects' task performance using the one-way repeated-measurement ANOVA to study how task performance varies with different thermal conditions. The result was shown in Table 5. While significant differences in performance were observed from some hard level tasks, no significant difference was found in the easy level task, indicating the effect of thermal environment on subjects' task performance could only be observed when the tasks are difficult.

We first examined the correlation between task performance and mental workload index using the Spearman's rank correlation coefficient for each type of task. The results showed that no correlation was found between the mental workload index and subjects' task performance. In other words, higher mental workload does not necessarily result in better performance because of the interference of the thermal environment [77]. Therefore, we used the ratio of task performance and mental workload to analyze how their relationship was affected by different thermal environments. The significant lower ratio in the slightly warm environment suggests lower task performance resulted from the same amount of mental workload. In other words, in the slightly warm environment, higher mental effort is needed to achieve the same performance as under the neutral and the slightly cool conditions. The slightly warm environment results in lower efficiency in the usage of subjects' brain resource and effort to their productivity gains.

These results correspond to findings from previous studies that high room temperature may cause a decrease in occupants' performance [21,25]. On the other hand, it was also suggested by Hancock and Vasmatzidis (2003) that people tend to maintain their performance when they have high motivation to perform well when the thermal stress is moderate [44]. Based on these findings, the increased mental workload found in this study could be interpreted as subjects trying to exert more effort onto the task to counteract the negative effect of high room temperature on their performance. In addition, as proposed by the "cognitive reserve" theory [19], subjects' have a certain amount of neural resources that are available to an activity. In this case, neural resources can be allocated to deal with cognitive tasks and thermal stress. When the resources are sufficient, the subject is able to maintain task performance while handling thermal stress. However, if the resources are deficient to handle both task performance and thermal stress, the performance will decrease. This explanation also justifies the result in Table 5 that no significant differences were found in the easy level tasks, while the decline in performance in the slightly warm environment was found in some hard level tasks.

The result further demonstrates the importance of a proper indoor thermal environment to occupants' well-being and performance [29]. In the long term, the continuous high mental workload demand would be detrimental to occupants' health. Meanwhile, occupants would lose their motivation to maintain their performance through extra effort over long periods of time [66]. In the future, we hope that this will help determine the optimal office thermal environment so that occupants' can maintain their work performance without exerting extra mental effort. It should be noted that the thermal environment setting needs to consider the individual differences of occupants in the room. A certain thermal environment should be set to cater to the thermal profile of the majority of occupants in the environment, which can be defined as an optimization problem to maximize the overall thermal comfort. This supports research in the area of human in the loop whereby researchers are identifying methods to increase human comfort by personalizing their environments [58,75]. Our research will also help support improved productivity.

5.4. Limitations

One of the limitations of working on EEG is that the brain signals are complex and could be affected by many factors, such as subjects' emotion and sleep. In this study, we increase the consistency of different experimental groups for comparison following the methods from previous studies [19,29,65–67]. For example, we conducted within-subject comparison only, asked subjects to fully engage in the tasks, and controlled several influential factors, such as the experiment time on each day, subjects' sleeping time, and clothing level. In the future, EEG signals can be supplemented by other physiological factor measurements to further eliminate the effect of other factors and improve the assessment approach.

Some other limitations of the EEG that affect the application of the proposed method in real office settings are listed as follows: first, in our pilot study, subjects reported that the EEG headset caused them headache after wearing it for about 30–40 min due to the tight clamping. Considering subjects' well-being and avoid discomfort influencing our experiment result, we removed the EEG headset from subjects for 15 min during the rest period between two cognitive task sessions. However, this will prevent us from monitoring subjects' mental workload continuously in real office work that typically lasts for several hours. Second, even though good connectivity was ensured at the start of the experiment, electrodes might have low connectivity or completely lose contact later in the experiment. In this experiment, we lost connectivity for two subjects and those were excluded from the analysis because the data collected did not have the adequate quality to be used for analysis. Furthermore, subjects need to stay in steady states while measuring the EEG to ensure the quality of the data. However, in real office settings, although workers were assigned a workstation, a considerable amount of movement was involved that prevents the EEG headset from collecting clean data.

Another limitation of this paper is that our proposed method was developed based on office environment settings. Therefore, only moderate thermal condition, from slightly cool (PMV = −1) to slightly warm (PMV = 1) was considered. The thermal stress posed on subjects may not be severe enough to affect their workload and task performance intensively. However, the proposed method could be used with a larger temperature range. It could also be applied to study the effect of other IEQ factors (e.g., lighting, air quality, etc.) on occupants.

6. Conclusions

In this paper, a novel method of using the EEG to investigate the effect of thermal environment on occupants' performance is proposed, by studying how thermal environments impact mental workload and evaluating how mental workload relates to occupants' performance. The main contribution of this paper is that the proposed method could be used to investigate the effect of environment on occupants which could not be reflected through task performance results directly. An index with adequate efficiency to reflect the mental workload was developed based on previous studies, accommodating to the limited number of electrodes on the low-cost EEG headset used in this study.

By comparing the index of mental workload measured by the EEG, along with its relationship with cognitive task results under different thermal conditions, the following main conclusions are reached. First, most subjects have higher mental workload in the slightly warm environment. However, whether the mental workload was lower in neutral or slightly cool condition depends on the subjects as well as the type of task. Second, the effect of thermal environment on mental workload varies with individuals. For each task, the mental workload of different individuals changes differently with thermal conditions. Third, due to the impact of thermal environment, higher mental workload exerted by the subject did not result in higher task performance on the same task. However, it was found that in the slightly warm environment, higher mental workload is needed for most subjects to achieve the same performance. Results from this study provide us with an insight into how mental workload and task performance vary with thermal conditions. The proposed method allows us to develop personal thermal profiles for occupants understanding each individual's mental workload response in different environments, which can be applied in energy simulation or thermal comfort management as it represents the dynamics of building occupants and also provides feedback on how to achieve comfort (e.g., change clothing, adjust setpoint) while conserving energy effectively [78–80].

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