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ABSTRACT

The thermal environment has a great influence on individuals' performance; however, factors such as one's motivation to perform well under experimental conditions cause difficulties in assessing how room temperature affect subjects' performance. One approach to overcome this problem is to understand the changes in individuals' neurophysiological conditions. This paper reports on the results of an experiment where electroencephalogram (EEG) data were collected from 5 subjects while they performed four computerized cognitive tasks. Power spectral density of EEG signals in three different thermal environments, slightly cool, neutral, and slightly warm, was compared within-subjects. In most cases, significant differences in PSD of the frontal theta (4-8Hz) activity are observed, indicating individuals' mental effort varies with room temperature. In the long run, the increased mental workload will reduce individuals' performance and be detrimental to their productivity. The study indicates that the proposed method could be implemented on a larger scale for further studies.

1. INTRODUCTION AND BACKGROUND

Temperature is one of the most important factors of indoor environmental quality (IEQ), which can significantly affect occupants' thermal comfort, health, and well-being (Li et al. 2017a). An undesirable thermal environment may lead to sick building syndrome symptoms such as eye, nose and throat irritation and affects occupants' performance and productivity (Witterseh et al. 2004). Previously, researchers investigated how different IEQ factors including lighting, acoustics, indoor air quality, and thermal comfort affect occupants' performance (Al Horr et al. 2016). Providing a comfortable work environment is considered an effective way to improve office workers' performance and well-being (Seppänen and Fisk 2006, Li et al. 2018). Meanwhile, it was shown that the high costs of improving those IEQ factors are offset by improved worker health (e.g., reduced absenteeism) and productivity (Djukanovic et al. 2002).

There are three most-commonly-used methods to measure the effect of IEQ on office workers' performance. The first method asks workers to subjectively rate their perceived performance (Tanabe et al. 2015). This method is convenient to implement and independent of the type of task. Although the rating is direct and comparable, it is highly biased and subjective. Therefore, this method has very limited value on evaluating the actual performance of occupants in different indoor environments. In the second method, workers' productivity in real working conditions is directly measured to evaluate their performance (Kekalainen et al. 2010); however, most office work (e.g., management, research) involves a variety of different tasks and skills and does not have clearly measurable and comparable output. Therefore, it is impractical to quantify office worker performance by directly measuring their productivity. The third method involves simulating office work using performance tests that represent the typical office activities in a laboratory environment (Lan et al. 2009). It enables us to directly understand the effect of IEQ on individuals' different cognitive and executive functions. Nevertheless, test results are significantly influenced by people's high motivation to perform better under experimental conditions (McCarney et al. 2007). In addition, experimental performance tests have short durations (e.g., range from 30 minutes to 2 hours) compared to real office work (e.g., 8 hours per day), which give subjects motivation to maintain high performance through the experiment.

Among all the IEQ factors, controlling room temperature is one of the simplest ways to achieve optimal workplace environments (Seppanen et al. 2005, Li et al. 2017b). Previous studies mainly focused on the effect of thermal environment on occupants' performance on the behavioral level, which is reflected by their productivity and psychometric test results (Toftum et al. 2005, Lan et al. 2009). However, subjects tend to maintain their performance under moderate thermal stress (typical of office environment) throughout the short experimental duration (Holm et al. 2009). Therefore, there are underlying changes in the occupants' neurophysiological level that are not reflected behaviorally, and thus could not be directly detected through the measurement of task performance (Hocking et al. 2001). In real office settings, neglecting these neurophysiological activities will eventually result in reduced long-term performance and detrimental health effects. As a result, developing a method to understand the neurophysiological effect of workplace thermal environment on workers' mental workload is of great significance. It could provide us with insights into setting workplace temperature in order to achieve the highest worker overall performance and well-being in the long run.

The objective of this paper is to understand how indoor thermal environment influences occupants' performance by investigating the neurophysiological effect of room temperature on subjects while they perform four different types of computerized cognitive tasks. In this paper, neurophysiological activity was measured using a low-cost, wireless EEG headset while the subjects performed tasks under three different thermal conditions, slightly warm, neutral and slightly cool, derived from Fanger's Predicted Mean Vote (PMV) model (Fanger 1970). After preprocessed the data, the PSD for each segment of data was obtained, and a within-subject comparison between PSD of the slightly cool/warm environment (PMV=-1/PMV=1) and PSD of the neutral environment (PMV=0) using the Wilcoxon signed-rank test was performed.

2. METHODOLOGY

In this study, a comprehensive framework was developed to study the neurophysiological effect of three different thermal environments on occupants, as shown in Figure 1. The temperature setpoints of the environment are based on the PMV model, representing the occupants' thermal sensation ranged from slightly cool to slightly warm. The subjects were asked to perform four selected cognitive tasks representing different cognitive functions (detailed in Section 2.1).

The neurophysiological activity was captured by Emotiv EPOC+, a low-cost wireless EEG headset that can record brain activities with reasonable quality. EEG is a non-invasive technique to monitor and record the electrical activities of the brain, typically through the electrodes placed on the scalp surface. By directly capturing the activities of the central nervous system, EEG can accurately reflect brain neural activities and subjects' cognitive states. EEG can capture the subtle variations in subjects' cognitive states with a high time resolution which cannot be reflected from subjects' behavioral responses (Cohen 2011). Several studies can be found using EEG to investigate the effect of temperature on individuals. However, Lan et al. (2010) and Yao et al. (2009) did not record the EEG signals in real-time while the occupants were performing tasks. Choi et al. (2019) asked subjects to study for their own work and did not control the difficulty of the task subjects performed under each thermal conditions.

To address the limitations mentioned above, in this study the EEG signal was measured at the same time while subjects were performing the given tasks with same difficulty levels and compared among three different moderate thermal conditions typical to the office environment.

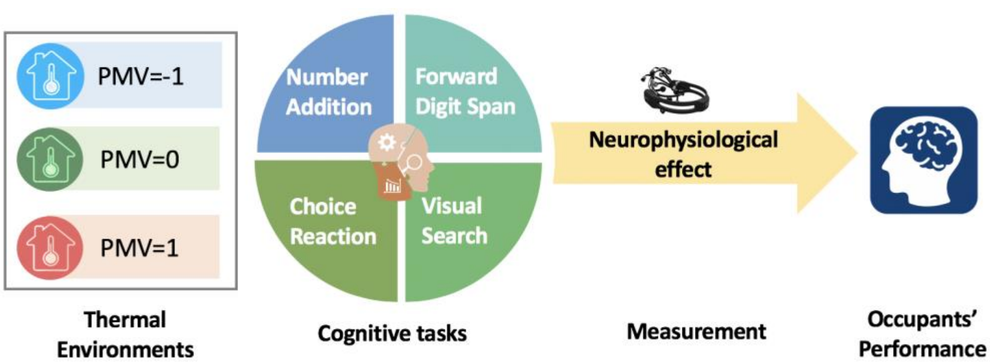

Figure 1: Framework to study the neurophysiological effect of the thermal environment

2.1 Cognitive tasks

In this study, we selected four computer-based cognitive tasks to arouse subjects' functions on thinking, working memory, perception, and choice reaction. All the tasks were developed with acceptable difficulty level for graduate students using the Javascript. The number addition (NA) task asked subjects to mentally add up columns of four 3-digit numbers (see Figure 2a) shown on the computer screen in a given time. In the digit span (DS) task, a sequence of eleven single-digit number series appeared on the screen one digit at a time (see Figure 2b). After all the digits showed up, subjects were asked to recall the number series and input it using the number pad. In the choice reaction (CR) task, the name of color appeared in the center of the screen one at a time. The subjects were requested to respond to the font color of the word as soon as possible regardless of the meaning of the word by pressing the first letter of the color on the keyboard (see Figure 2c). The visual search (VS) task required subjects to rapidly and accurately search for the target object on the right side of the screen from the 9x9 grid on the left side of the screen (see Figure 2d). All trials in the four tasks were randomly generated by a computer to ensure that the task difficulties remained the same each time it was conducted.

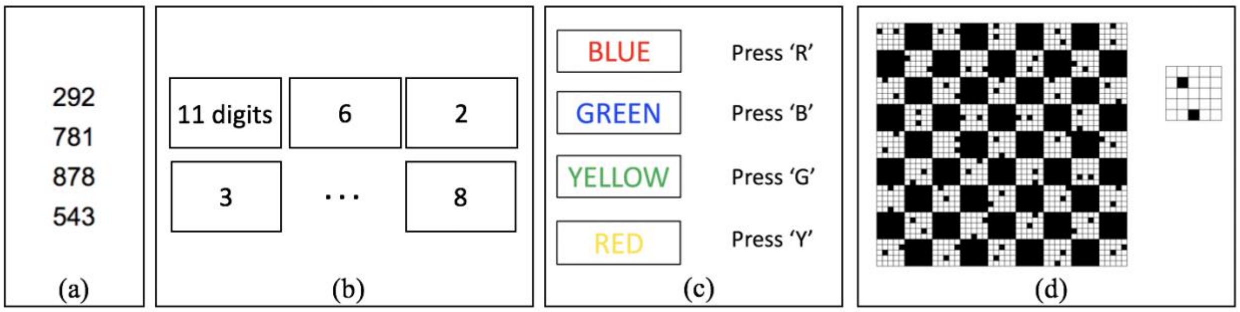

Figure 2: Overview of Cognitive tasks (a) Number addition (b) Digit Span (c) Choice Reaction (d) Visual Search

2.2 Experiment design

In our experiment, the temperature settings were derived from the PMV model, which is an international standard to evaluate the occupants' indoor thermal comfort based on the human body's thermal balance equation (Fanger 1970). Given the fact that the temperature in an office environment is usually controlled within a moderate range, we set the thermal condition to be PMV=-1 (69.8 °F/21 ℃), PMV=0 (76.3 °F/24.61 ℃), and PMV=1 (82.7 °F/28.17 ℃), which corresponds to slightly cool, neutral, and slightly warm on the ASHRAE thermal sensation scale, respectively. The experimental protocol was approved by the Institutional Review Board at the University of Michigan. All subjects recruited were graduate students. Each subject was required to participate in the experiment at the same time every day for three consecutive days with same clothing level and good rest the night before to eliminate the circadian effects.

In each experimental condition, the subjects followed the procedures shown in Figure 3. Before the experiment started, the subjects spent 30 minutes relaxing to adapt to the environment. Then, the authors had 15 minutes to set up the EEG headset on subjects with a good connection. The four cognitive tasks were divided into two sections, with two in each section. The order of the cognitive tasks was randomly shuffled among different subjects, while each subject performed the tasks in the same order on different days. Between the two cognitive task sections, the subjects had a fifteen-minute rest with the EEG headset removed from their heads. After the cognitive tasks, the subjects conducted a short survey about their thermal sensation and thermal comfort in the experiment. Due to the scope of this paper which focuses on the EEG data itself and its analysis, the results of this survey will not be discussed.

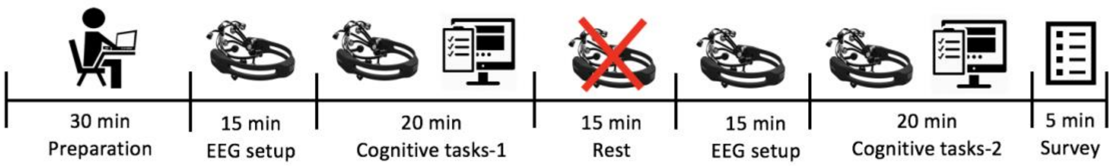

Figure 3: Experiment procedure for each day

2.3 Data analysis

The raw EEG data collected were divided into segments according to the start and end time the subjects conducted the task recorded by the computer. Each segment corresponds to the dataset of a subject to perform a task in a thermal environment. To preprocess the raw data, we first removed the DC (direct current) offset and limited the slew rate. Next, the finite impulse response bandpass filter with 1 Hz low-pass and 55 Hz high-pass was applied to remove extrinsic artifacts from the data. Eye artifacts (i.e. eye blink, eye movement) and muscular artifacts were removed by implementing the Independent Component Analysis algorithm (Comon 1994). After that, we calculated the PSD for each dataset. PSD is the power of the signal as a function of frequency. In our study, we used the Welch's average periodogram method with Hanning window that returns 2048 discrete Fourier Transform points. Since the previous study suggested that theta band power (4-8 Hz) of frontal region increases with the growing task demands, which require higher mental effort, and the left cerebrum hemisphere is detail-oriented and responsible for the logical, mathematical and scientific skills (Holm et al. 2009, Klimesch 1999), we only focused on the PSD in theta frequency band of the F3 channel (placed over the left frontal lobe). The Wilcoxon signed-rank test was then used to compare PSD of the same type of task in different thermal environments within-subject because different subjects' individual differences cause their EEG signal patterns not comparable to each other.

3. RESULTS

For each dataset, we calculated the PSD and selected 65 data points with an equal interval (1/16 Hz) in the theta frequency band. The Wilcoxon signed-rank test was used to compare the theta PSD of the neutral thermal environment (PMV=0) to the slightly cool (PMV=-1) and slightly warm (PMV=1) environments for each type of task. The mean PSD is given in Table 1. Values in bold means the PSD of that dataset is significantly different ($p<0.05$) with the PSD in the corresponding neutral environment (PMV=0). In most cases, significant differences could be observed on theta band PSD of the F3 channel when thermal condition went from neutral to slightly cool or slightly warm. Since frontal theta PSD is positively correlated with task demands and subjects' mental effort exerted, we concluded that subjects had different mental workloads in different thermal environments even though task demands are the same. Therefore, the method enabled us to understand how thermal environment influence office workers' performance through its effect on their neurophysiological activities.

Bar charts in Figure 4 show the change of mean frontal theta PSD for each subject on different types of tasks. In most cases, subjects' mean PSD was relatively low when PMV=0, which implies relatively less mental effort was spent in the neutral thermal condition. It could be found that subjects have different sensitivity to the room temperature. For example, Subject 2 was not sensitive to the slightly warm environment since his/her frontal theta PSD have little difference for all types of tasks. The effect of the thermal environment also depends on the task type. Taking Subject 5 for example, he/she was very sensitive when the thermal condition deviated from neutral for the number addition, digit span and visual search task. However, his/her PSD did not change significantly for the choice reaction task. In addition, he/she had lower mental workload in the cooler environment than in the warmer one for the digit span and visual search task, while vice versa for the other two tasks.

Table 1: The Wilcoxon signed-rank test results

	Subject 1			Subject 2			Subject 3			Subject 4			Subject 5		
PMV	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1
NA	2.324	2.007	**1.267**	0.570	0.589	0.689	0.372	**1.752**	**0.761**	1.486	**1.920**	**1.393**	1.392	**2.497**	**2.198**
DS	1.543	1.439	1.525	0.632	**2.026**	0.565	0.587	**1.183**	0.636	1.381	**2.465**	1.143	0.885	**1.559**	**2.673**
CR	1.884	**1.495**	**2.879**	0.781	**1.065**	0.682	0.455	**1.352**	**0.828**	1.358	1.451	**0.980**	1.044	1.281	0.849
VS	1.628	**1.436**	**2.883**	0.507	**1.810**	0.389	0.516	**1.249**	**0.633**	1.542	**2.556**	1.684	0.439	**1.038**	**1.670**

Bold represents a significant difference (p<0.05)

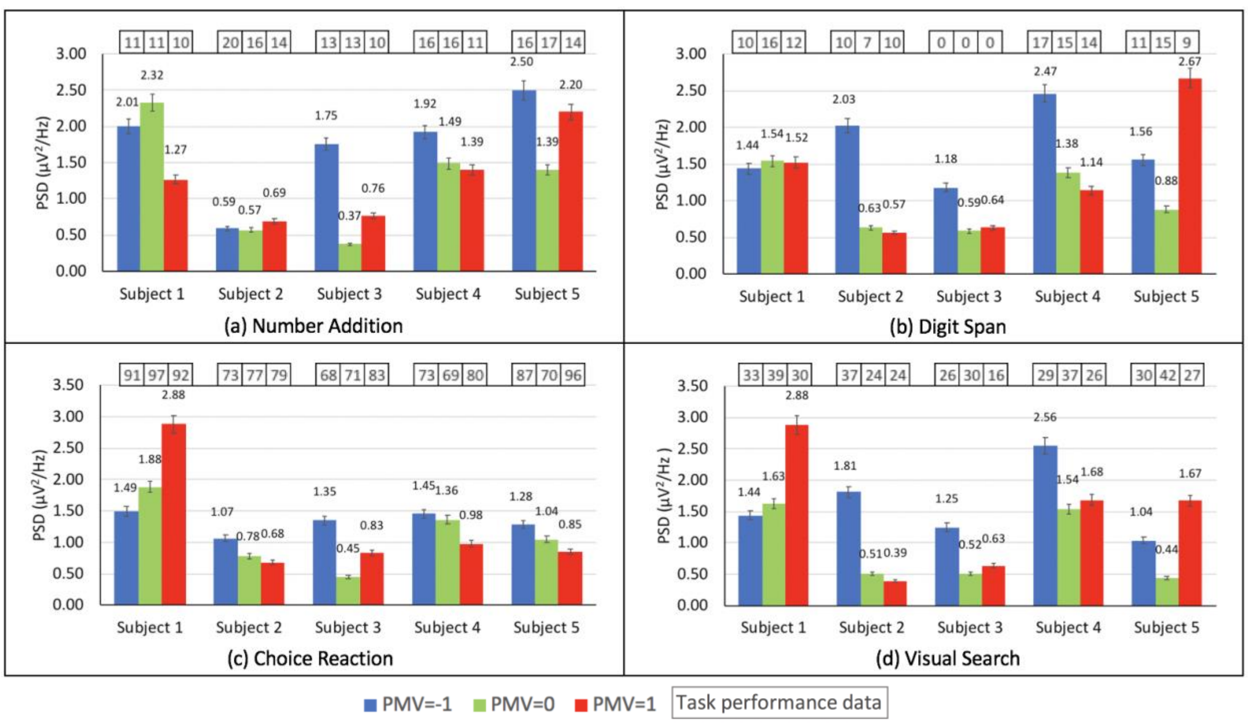

Figure 4: Mean PSD and task performance comparison for each task

Subjects' task performance data are shown in the tables above the bar charts. We used the average response time (10ms) for correct responses to quantify subjects' task performance for the choice reaction task and the number of correct trials to quantify performance for the other three tasks. In most cases, subjects had the worst performance in the slightly warm environment and better performance in the neutral or the slightly cool environment. It could be found that additional mental effort exerted did not necessarily result in better performance on the tasks, which warrants additional data analysis which is part of our future work.

4. CONCLUSIONS

In this study, we proposed a method to measure the neurophysiological effect of thermal environments on individuals when they were performing different types of cognitive tasks. Based on the conclusion of the previous study that frontal theta PSD raised with increasing task demands and higher mental workload, we investigated how thermal environment affect subjects' performance by studying its effect from the neurophysiological perspective. Even though the task difficulties remained the same in different thermal conditions, the tasks had different demands on subjects' mental effort when the thermal conditions varied and subjects tend to have worse performance in the slightly warm environment. We also found that subjects did not achieve better performance with higher mental effort. The study shows the potential of using the neurophysiological effect measured by the EEG to acquire optimal office environments so as to achieve the lowest workers' mental workload considering individual differences and types of work they are performing. A limitation of the proposed method is that the subjects need to be relatively static while performing tasks to keep the EEG data clean. In the future, more elaborate index to reflect mental effort could be reached by including more EEG channels and wider frequency range, which will enable us to dive deeper into the effect of temperature on individuals' performance by studying on more subjects.

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