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Effect of temperature on attention ability based on electroencephalogram measurements

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ABSTRACT

In this study, subjects' attention abilities in seven predicted mean vote (PMV) conditions (−3 to +3) were measured using electroencephalograms (EEGs). A total of 49 EEG recordings were performed (in seven PMV conditions for seven subjects), each lasting for 65 min. EEGs were recorded through the scalp and sorted by frequency using power spectral analysis. The best PMV condition for attention ability changed over time, from slightly cooler temperatures to higher temperatures. However, extreme PMV conditions led to poor attention ability during the experiment. The highest attention level was at PMV +1, according to our EEG analysis, but was reported as both PMV 0 and + 1 by the subjects. The lowest attention level was in higher temperature conditions (PMV +2, +3), according to subjects' own evaluations, while the lowest brain activity was measured in lower temperature conditions (PMV -2, −3).

1. Introduction

This study was conducted to evaluate occupants' attention ability in seven predicted mean vote (PMV) conditions (from −3 to +3), based on electroencephalogram (EEG) measurements. Attention is the cognitive process of concentrating to complete a certain task within a specific time span [1]. Previous studies have explored the effect of the indoor thermal environment on occupants' attention, using paper-based or computer-based test scores to measure attention ability [2–5]. Recently, many studies exploring attention ability using EEG measurements have been published in the fields of education, physical education, and ergonomics [6–9]. Thus, it may be valuable to measure attention-related brain activity by EEG for indoor environmental quality research. The adequate method for measuring productivity has been a topic of debate in prior studies [10,25]. In this study, attention ability was measured by EEG as a metric of productivity, instead of measuring productivity itself.

EEG is the recording of electrical activity on the surface of the scalp. It is divided into delta (0–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz) waves by frequency. In this study, sensorimotor rhythm (SMR) waves were used to examine attention abilities. SMR waves are in the frequency range of 12–15 Hz, covering both alpha and beta waves. This frequency range is a well-known attention-related range [11]. Additionally, middle beta waves (16–20 Hz) often occur during active mental activity, such as learning, memorizing, or computing. In this study, a specific power ratio of these two waves ([SMR + Middle Beta]/Theta) was used to analyze the subjects' attention levels [12].

2. Methods

2.1. Experimental conditions

Seven male volunteer students (age: 22–28 years) participated in the study and received monetary compensation. Their participation was approved by the Institutional Review Board (IRB) at Yonsei University. The health condition of the subjects was tested using the “Self-fatigue assessment tool” developed by the “Japanese Society for Occupational Health” [13]. This assessment was performed prior to every experiment. Additionally, the subjects reported that they had never been diagnosed with a brain disease. Female subjects were not included in this study because the menstrual cycle may affect thermal sensation and other outcomes when the duration of the experiment is more than one month. All experiments were conducted during daytime, except for the early-morning and evening sessions. The order of the experiments and the time-frame were considered and counterbalanced among subjects.

Experiments were performed in a climate chamber at the university. The experiments were conducted between September 24 and October 29, 2013. The average outdoor temperature was 16.6 °C and the relative humidity was 59.7%. Experimental environments were constructed

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Table 1
Conditions of the climate chamber for each predicted mean vote (PMV).

PMV	Air temperature (°C)	
	Set	Actual
−3	14.60	14.79 ± 0.06
−2	17.80	17.92 ± 0.06
−1	21.10	21.12 ± 0.03
0	24.40	24.40 ± 0.01
+1	27.60	27.47 ± 0.06
+2	30.80	30.81 ± 0.00
+3	33.80	33.80 ± 0.03

using seven PMV conditions. Air temperatures were as shown in Table 1 and other conditions were fixed at 50% relative humidity, 0.1 m/s air velocity, 0.8 Clo value (training suit, electrode cap, and office chair), and 1.0 met of metabolism. The pre-chamber before the experiment was set to neutral conditions (24.4 °C, PMV 0). The features of the climate chamber are shown in Fig. 1.

2.2. Measuring tools: EEG recording system

The EEG was recorded with Ag/AgCl electrodes from eight scalp locations according to the international 10–20 system with an electrode cap [14]. The right earlobe served as reference. The recording locations included four lateral sites at the left of the midline (Fp1, F3, T3, and P3) and their corresponding sites on the right of the midline, as shown in Fig. 2. The electrooculogram was recorded to correct for artifacts, including blinks and eye movement, with a disposable surface electrode (Tyco Healthcare Group LP, Norwalk, CT, USA). All signals were recorded with the bio-signal instrumentation system MP150 (Biopac System Inc., Santa Barbara, CA, USA). A 0.1–35-Hz band-pass filter was used for all online recordings. EEG and electrooculogram were sampled at 1000 Hz. A Power Spectral Density, using the "BrainMap-3D" S/W (Laxtha, Daejeon, Korea), was computed to divide the raw EEG signal into the three following frequencies: theta (4–8 Hz), SMR (12–15 Hz), and Middle beta (16–20 Hz). These were used to compute the attention level ([SMR + Middle beta]/theta) as described above.

2.3. Experimental procedures

All subjects experienced seven conditions over seven days and each subject was exposed to one condition per day. Subjects attached the EEG electrodes after clothing themselves in sweatshirts and pants in the neutral environment pre-chamber. Afterwards, they waited for 15 min in a neutral environment for adaptation. They then moved to the climate chamber and their electrodes were connected to a computer. During the experiment duration of 65 min, the subjects were asked to study. After measuring the EEG for 65 min, the subjects were asked to answer a question regarding perceived attention ability, i.e., how well they concentrated, from "Could not concentrate at all" to "Concentrated very well." To exclude order effects, all subjects' experimental condition orders were different, as shown in Table 2. A total of 49 experiments were conducted.

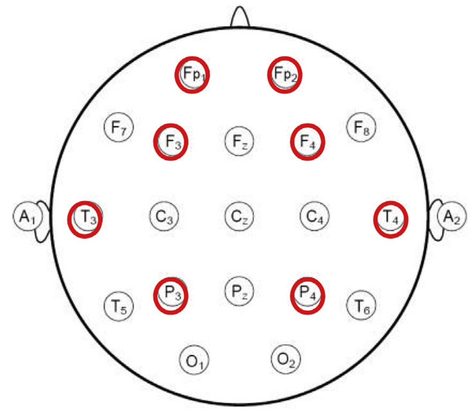


Fig. 2. International 10–20 system of electrode placement.

3. Results

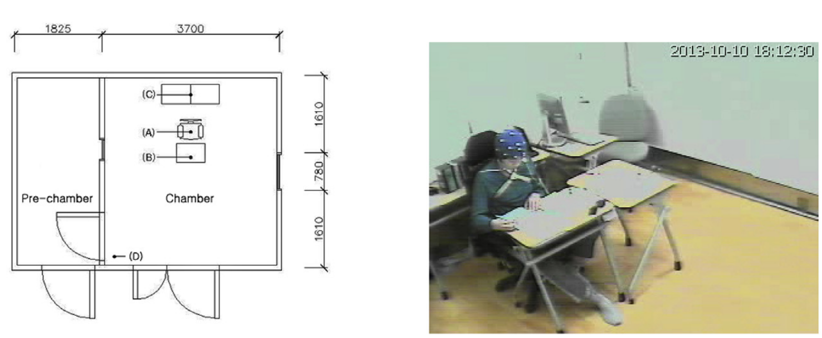
Among eight measured EEG channels, power from the prefrontal channels (Fp1 and Fp2) was analyzed as in previous studies that calculated [SMR + Middle beta]/theta value [12,15,16]. The best PMV condition for attention ability was shown to change over time (Fig. 3). The EEG power value was strongest in PMV -1 for the first 30 min, and in PMV 0 for the last 30 min. Finally, at the end of the experiment, the EEG power value in PMV +1 increased rapidly. PMV -3 was the worst condition for attention throughout the experiment. For a clearer visualization of the results, the graph was divided into data for mild temperatures (PMV +1, 0, −1), which showed stronger EEG power values, and data for other extreme temperatures (PMV +3, +2, −3, −2) (Figs. 4 and 5).

3.1. Attention ability at mild temperatures

The EEG power value is shown by Fp1 (Left) and Fp2 (Right) in separate graphs. Both areas showed similar tendencies. The EEG power value was strongest in PMV -1 for the first 30 min, and in PMV 0 for the last 30 min. Before the end of experiment, the highest EEG power was observed in a warmer condition, PMV +1.

3.2. Attention ability at extreme temperatures

For this analysis, attention ability was measured at PMV +3, +2,



a) Plan of chamber (A) chair (B) desk (C) MP150 (D) CCTV b) Electroencephalogram electrodes connected to a patient

Fig. 1. Features of the experimental chamber.

Table 2
Order of the experiments for each subject.

	1st	2nd	3rd	4th	5th	6th	7th
Subject A	PMV -3	PMV -2	PMV -1	PMV 0	PMV +1	PMV +2	PMV +3
Subject B	PMV -2	PMV -1	PMV 0	PMV +1	PMV +2	PMV +3	PMV -3
Subject C	PMV -1	PMV 0	PMV +1	PMV +2	PMV +3	PMV -3	PMV -2
Subject D	PMV 0	PMV +1	PMV +2	PMV +3	PMV -3	PMV -2	PMV -1
Subject E	PMV +1	PMV +2	PMV +3	PMV -3	PMV -2	PMV -1	PMV 0
Subject F	PMV +2	PMV +3	PMV -3	PMV -2	PMV -1	PMV 0	PMV +1
Subject G	PMV +3	PMV -3	PMV -2	PMV -1	PMV 0	PMV +1	PMV +2

−3, and −2. Figs. 6 and 7 show the attention ability in the extreme temperature zone at both Fp1 and Fp2. In extreme conditions, the EEG power value was strongest in PMV -2 during the first 30 min, and in PMV +2 for the last 30 min. This was similar to the tendency observed at mild temperatures. Relatively low temperatures are better for attention at first, but warmer conditions become better for attention later in the session. The time for this change was faster (25 min) in extreme conditions than at mild temperatures (30 min). PMV -3 showed the worst EEG power values for the duration of the experiment.

3.3. Comparison with perceived attention

Fig. 8 shows the average EEG power value ([SMR + Middle beta]/theta) during the 60-min experiment, and Fig. 9 shows the subjects' evaluation of perceived attention after the experiment (0; could not concentrate at all, 6; concentrated very well). Brain activity seems comparable to the perceived attention. However, the highest attention level was in PMV +1, according to EEG analysis, but in both PMV 0 and + 1, according to perceived attention. The lowest attention level was at higher temperatures (PMV +2, +3), according to subjects' evaluations, while the lowest brain activity was at low temperatures (PMV -2, −3).

4. Discussion

The impact of the thermal environment on work performance has conventionally been studied by evaluating productivity. Productivity is defined as the extent to which activities are performed based on the goals [17]. Objective human productivity under different thermal environments has been quantified by performance in field-based or lab-based observations. In terms of field-based observations, work performance in either a call center or a factory was used, because productivity can be easily quantified in these settings. Niemela et al. [18] investigated the effect of air temperature on labor productivity by monitoring the number of telephone calls divided by the active work time in telecommunication offices. They found that productivity falls by 5–7% when air temperature exceeds 25.8 °C. Ye et al. [19] carried out a field survey in a factory to investigate the relationship between employee productivity and the thermal environment. Slightly cool temperatures in the building were more likely to have active or positive effects on productivity. Tham and Willem [20] measured the impact of temperature on call-handling performance. Decreasing temperature from a marginally warm thermal sensation to a marginally cool thermal sensation (at low ventilation rates) improved operator talk performance by between 5 and 13%. Federspiel et al. [21] measured the productivity of call center workers in the US. They found no significant effect of temperature on productivity within the comfort zone. Lan et al. [22] found that performance in neurobehavioral tests decreased when the thermal environment deviated from neutral conditions. Participants experienced more negative emotions and needed to exert more effort to maintain their performance under moderately adverse (slightly warm or slightly cool) environmental conditions. From these studies, the common findings are that productivity is decreased when temperature exceeds that of the comfort zone. Furthermore, a slightly cool environment shows positive effects on productivity. In this study, we found that a slightly cool temperature increased attention ability in the first part of the experiment, as in previous studies, but the best temperature for attention increased over time.

Productivity studies in the laboratory mainly used cognitive tasks, such as memory and computation tasks, to quantify productivity. Johansson [23] exposed subjects to a climate chamber of effective temperatures of 24 °C, 27 °C, and 30 °C. Several tests were used to evaluate the effect of the thermal environment on performance. Most tasks, except cue utilization and similar perceptual and non-motor tasks, were impaired at the two higher temperatures. Perceptual tasks measuring cue-utilization and attention had an inverted U-shape

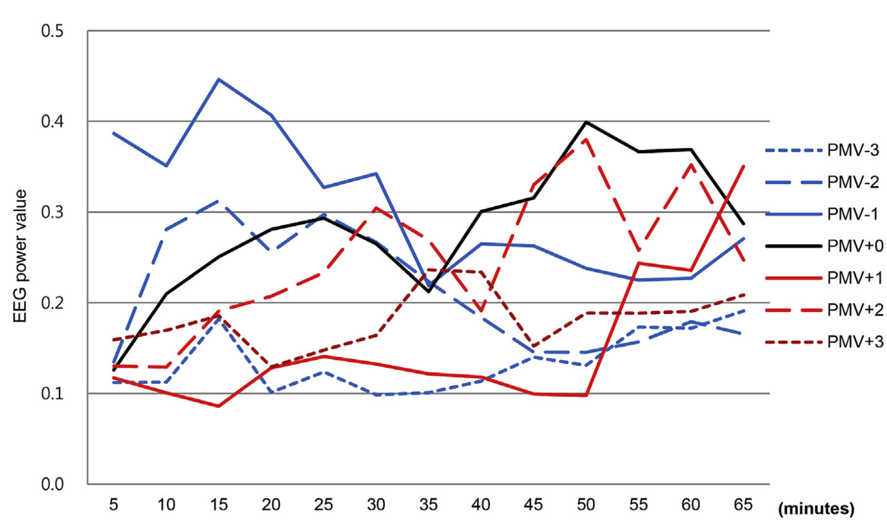


Fig. 3. Attention ability over time (prefrontal average).

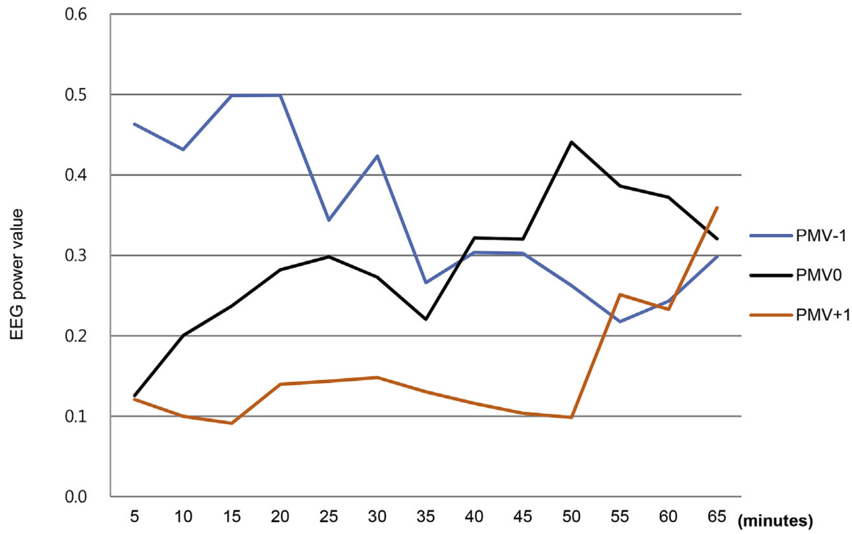


Fig. 4. Attention ability at mild temperatures over time (Fp1; left prefrontal).

relationship with temperature, with the best performance at 27 °C. Witterseh et al. [24] investigated the effect of temperature on simulated office work (including multiplication, typing, and addition tests), and found no significant effect of temperature on performance, when it was increased from thermal neutral temperature (22 °C) to a slightly warm discomfort temperature (25 °C). Lan et al. [25] performed neurobehavioral tests at four temperatures in the laboratory and found that room temperature differentially affects performance, depending on the type of task. Lorsch [26] reported that there is a critical temperature zone (between 32.2 °C and 35 °C), above which the accuracy of mental tasks declines. These laboratory studies yielded similar results to field studies, in which near comfort zone temperatures had positive effects and extremely high temperatures had negative effects on productivity. Furthermore, temperature differentially affects productivity according to the type of work.

In productivity studies, it has been a challenge to determine how to measure productivity accurately, as there are many work types. In this study, we focused on attention ability itself, which appears to have solved this problem. Attention ability is easier to measure objectively because it can be measured using physiological signals, such as EEG power. Studies involving EEG are not common in analyses of thermal comfort. Yao et al. [27] measured heart-rate variability and EEG in relation to thermal comfort, using a pair of electrodes to measure the right side of the head and the center of the forehead. They found that the lowest global relative EEG power of beta waves is achieved under neutral thermal sensation, while the highest global relative EEG power of alpha waves is achieved when subjects feel slightly cool. Lan et al. [28] found that participants had lower motivation to perform work and that their EEG delta waves decreased in a moderately uncomfortable environment. Shan et al. [29] observed that EEG frontal asymmetrical activity is correlated to a subjective questionnaire and objective task performance. Neutral thermal conditions lead to a more positive approach than other thermal conditions. Additionally, self-perceived performance does not correlate well to actual performance. In our study, we found that extreme conditions negatively affected attention and that there is a gap between perceived attention and physiologically measured attention. Perceived attention after the experiment was worst at higher temperatures (PMV +2, +3), but measured EEG was worst at lower temperatures (PMV -2, −3). Moreover, the highest attention level was in PMV +1, according to EEG analysis, but in both PMV 0 and + 1, according to the subjects' evaluations, indicating that people do not know the optimum temperature for their attention ability or the temperature at which their attention was the best. Leaman and Bordass showed a difference in perceived productivity between occupants who

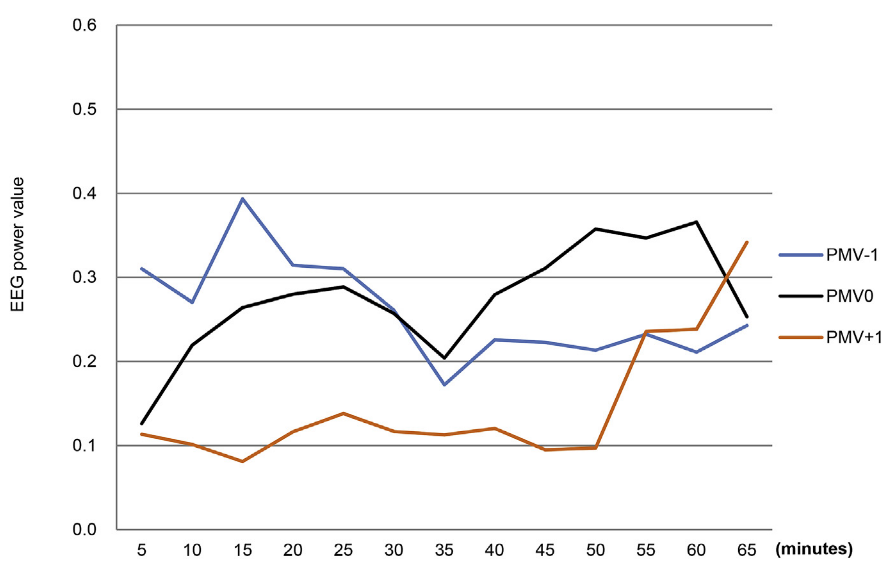


Fig. 5. Attention ability at mild temperatures over time (Fp2; right prefrontal).

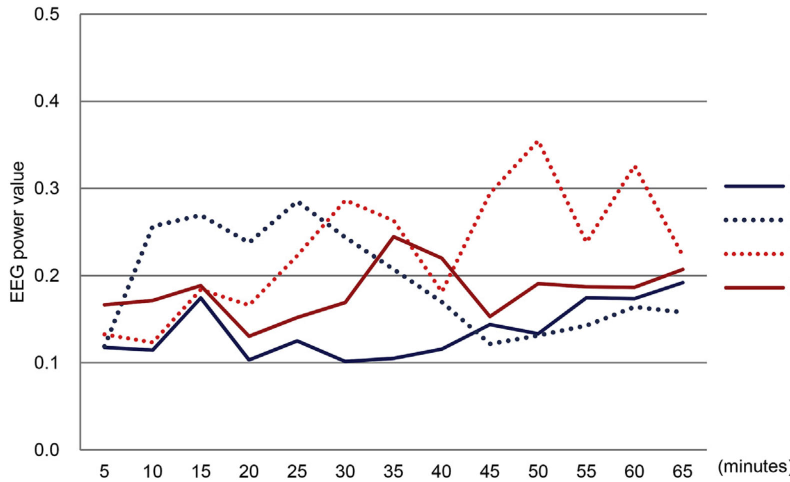


Fig. 6. Attention ability at extreme temperatures over time (Fp1; left prefrontal).

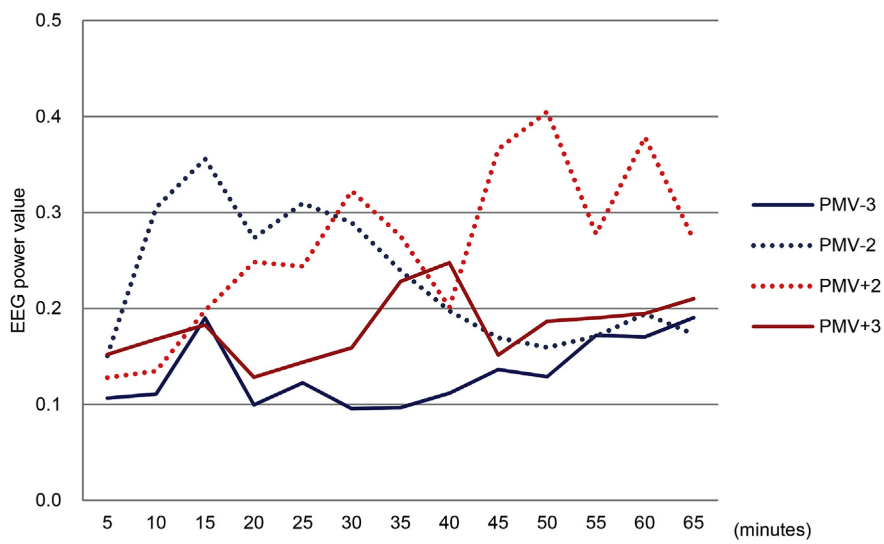


Fig. 7. Attention ability at extreme temperatures over time (Fp2; right prefrontal).

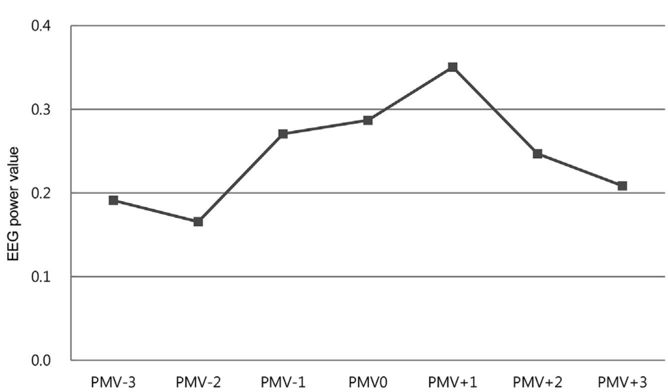


Fig. 8. Electroencephalogram (EEG) power value in the prefrontal lobe in each predicted mean vote (PMV) condition (average over 60 min).

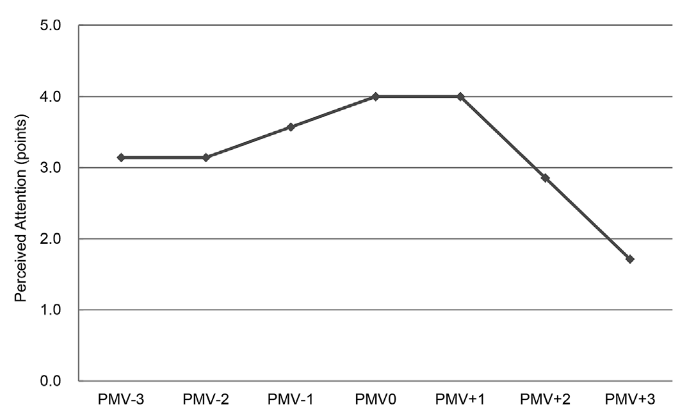


Fig. 9. Subjects' evaluation of perceived attention in each predicted mean vote (PMV) condition after the experiment.

reported that their building was comfortable and those describing their building as uncomfortable. Uncomfortable staff reported their productivity to be worse [30]. Perceived productivity may be biased by the influence of thermal comfort. However, the best temperature for productivity is not always the same as the comfortable temperature. Some researchers claim that thermal conditions providing thermal comfort do not provide the maximum efficiency [31]. Hence, the temperature needs to be balanced between comfort and productivity needs.

Traditionally, thermal comfort studies have focused on finding the optimal temperature for comfort. However, optimal thermal comfort and optimum performance may not coincide, depending on the particular type of task. For example, creative mental work may require a similar optimal thermal temperature and optimum performance temperature, but another type of mental work may require a slightly colder temperature for optimum productivity [32,33].

The thermal environment is not only important for the individual's comfort but also for the occupant's behavior, health, and well-being. Current research is mostly focused on supporting the occupant's attention for better learning or work, but more studies are needed to investigate the effects of the thermal environment on health and behaviors of occupants. Another potential topic of future studies is the influence of age on the effects of the thermal environment. The participants in this study were younger than 30 years, but the thermal environment may cause some effects in this population that are different from those in middle-aged adults and individuals of other age groups.

5. Conclusions

This study was conducted in various indoor air temperature environments, arranged according to PMV. We used EEG measurements to investigate the effect of indoor air temperature on occupants' attention abilities, resulting in the following observations:

1. A relatively lower temperature was advantageous for attention at the beginning of experiment. However, a higher temperature was advantageous for maintaining attention after 25 min (in extreme conditions) or 30 min (in moderate conditions).
2. Attention enhancement was best early in the PMV -1 condition. This effect decreased over time. After 1 h, there was no substantial difference among PMV -1, 0, and +1. PMV +1 was the most optimal condition for attention at the end.
3. Perceived attention according to subjects' evaluation differed from that indicated by brain activity. Subjects answered that PMV 0 and PMV +1 were both best for attention, but brain activity indicated the best attention at PMV +1. Additionally, the lowest attention levels were recorded at higher temperatures (PMV +2, +3) from subjects' evaluations, while the lowest brain activity was recorded at low temperatures (PMV -2, −3).

This study objectively measured productivity by measuring attention ability itself, rather than the subjects' evaluation or limited types of work. The measurement of physiological signals via EEG allowed to quantify results. Attention is the foundation for many types of work, so this may be the best method to measure productivity. Subjective evaluation is important to evaluate the effects of the thermal environment on productivity. However, there was a gap between subjective evaluation and measurement of brain activity. Because of this result, EEG can be a useful and objective method to measure occupants' attention and productivity levels.

Acknowledgments

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