Electroencephalography associated with thermal discomfort induced by temperature upward ramping

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ABSTRACT

This study investigates the brainwaves associated with thermal discomfort induced by temperature upward ramping. This experiment was conducted on 35 university students. Participants stayed for 40 minutes in a climate chamber where the temperature gradually increased, and at the same time, EEG measurements and thermal comfort answers were performed. As a result of the temperature increasing, the participants felt uncomfortable and the relative power value of all frequency bands gradually increased. As a result of correlation analysis of individual thermal comfort change and relative power change, the alpha power at Cz, C3, the beta power at Fz, Cz, and C4 and the gamma power at C4 increased.

INTRODUCTION

Brainwave is a physiological signal recorded by amplifying microscopic electrical activity of the brain on the scalp. An electroencephalogram (EEG) records the potential difference between the electrodes by attaching electrodes to the scalp to induce and amplify the variation of the microscopic potential generated by changes in the brain's nervous system activity (Lee, 2011). EEG is related to concentration, arousal, stress, and various other mental activities (Sanei and Chambers, 2007), and through EEG, human cognition, emotions, and psychological states can be identified. Brain waves can be classified into delta waves, theta waves, alpha waves, beta waves, and gamma waves in order from low to high frequencies according to frequency characteristics.

Brainwaves have recently attracted attention as an index that can measure thermal comfort. In a previous study (Yao et al., 2009) examining heart rate variation and EEG according to thermal comfort, thermal sensation was collected under four temperature conditions. Alpha waves were significantly different in each temperature condition, and beta waves and theta waves were also partially significant. Beta wave was inversely proportional to thermal sensation, alpha wave was highest in slight cool and decreased in uncomfortable thermal environment, and theta wave was highest in neutral.

Studies that investigated changes in EEG at 23, 26, and 29℃ also showed that EEG frontal asymmetry activity is related to subjective response and task performance (Shan et al., 2018).

However, these previous studies collected thermal sensation based on PMV, and did not survey thermal comfort. Although the PMV model can show the correlation between the thermal environment conditions and thermal sensation well, it cannot essentially explain what human comfort is (Yao et al., 2009).

In a study that measured EEG in two subway stations where comfort was sharply contrasted, beta and gamma waves were high when people responded as uncomfortable (Kim et al., 2020). There was also a study that showed a high correlation between EEG and thermal sensation vote overall, and relatively low correlation between thermal comfort vote (Han et al., 2004). However, the preceding studies above analyzed the EEG after being in the room for a certain period of time, so the EEG at the moment when the feeling of comfort or sensation changed could not be confirmed.

A previous study examining the relationship between EEG and thermal pleasure mentioned that the relative theta power at the Fz region increased significantly when the occupant felt thermal pleasure caused by a rapid temperature change (Son and Chun, 2018). In this study, changes in EEG according to thermal pleasure could be identified for each measuring point and frequency, but since the experimental condition was the induction of a thermal comfort according to the down-step temperature, it was not possible to know how EEG appeared under other environmental change conditions.

Therefore, in previous studies, as a result of examining changes in EEG according to thermal displeasure (Han & Chun, 2020), thermal displeasure was induced according to heat and cold, and the difference in frequency and region of EEG was statistically significant. Previous studies induced thermal displeasure according to sudden temperature changes, but this study aimed to cause thermal discomfort according to gradual temperature changes and to examine changes in EEG.

The aim of this study examines the EEG patterns according to the thermal discomfort of the occupants with gradual temperature increasing by identifying the moment of participants perceiving “hot” or “uncomfortable” and measuring the changes in EEG at that moment.

METHODS

- *Subjects*

18 men and 17 women in their 20s and 30s participated in the experiment. The experiment was approved by the Yonsei University Institutional Review Board (IRB), and an explanation of the experiment process was made before the experiment was conducted for the participants. In the event that the participants of the experiment decided that they would not be able to continue their participation due to strain or discomfort in the thermal environment, they were informed that they could ask the researcher to stop at any time. In addition, the participants of the experiment were restricted from excessive exercise, alcohol consumption, and excessive activities that cause physical fatigue the day before the experiment.

All participants of the experiment wore the same clothing (underwear, long-sleeved top, long-sleeved bottoms, socks).

- *Experimental conditions*

In this experiment, thermal discomfort and EEG patterns were examined when a gradual temperature change from a comfortable environment to an uncomfortable environment occurred. The pre-chamber was used to stabilize the physical condition of the participants, and the experiment was conducted in the climate chamber.

The experimental conditions are as follows. The environmental conditions of the pre-chamber were set to an air temperature of 25℃ and relative humidity of 50%, which is the state of PMV(Predicted Mean Vote) 0, and the initial environment of the climate chamber was also the same as that of the pre-chamber.

For comparing the EEG in a comfortable environment with that of the moment of changing to an uncomfortable environment, the indoor environment was maintained at the air temperature of 25°C and the relative humidity of 50% for 10 minutes after the start of the experiment. After that, the temperature and humidity were gradually changed so that participants could experience the change from a comfortable environment to a very uncomfortable environment. At the end of the experiment, the set value of the air temperature was 32°C and the relative humidity was 65%.

During the experiment, the average value of the internally measured values was 24.9°C at the start and 56% relative humidity. At the end of the experiment, the air temperature was 31.9°C and the relative humidity was 58.8% (Figure 1). Due to the setting of the experimental conditions with a large temperature change, there was a limit to the operation of the HVAC system, so the control of the relative humidity was not well regulated.

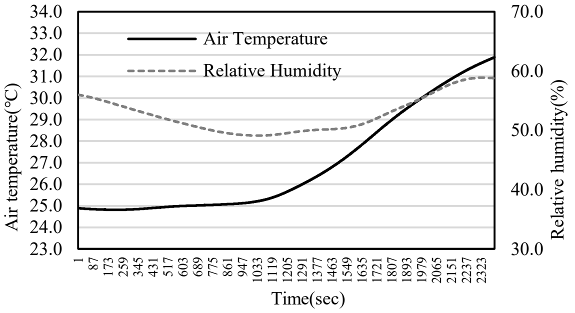

Figure 1. Temperature and humidity change in the experiment

- *Measurement tools*

In order to measure the psychological responses of the participants according to the gradual change of the thermal environment, a questionnaire of two items was conducted, thermal sensation and thermal comfort. In this experiment, the participant had to feel the heat gradually in a comfortable state and feel discomfort so it had to be premised that the thermal sensation before the start of the experiment was in a neutral state and felt comfortable. To investigate this, the thermal sensation and thermal comfort surveys were conducted before the start of the experiment. With this experiment, since the temperature and humidity were gradually rising, it was composed of a one-way 4 point scale of Neutral-Slightly hot-Hot-Very hot, except for the "cold" side scale, unlike the general thermal sensation scale. And the thermal comfort scale was composed of a 5 point scale; Comfortable-Slightly comfortable-Slightly uncomfortable-Uncomfortable-Very uncomfortable.

The thermal sensation after the start of the experiment was recorded through ComVote(Kwon, 2018). ComVote can continuously measure air temperature and humidity at the set interval, and is a device that can record and store time, air temperature, and humidity the moment the user presses the voting button. In this experiment, it was important to check when the participants felt hot, so the questionnaire was conducted using ComVote, which records the time to respond to the questionnaire and the indoor environment value at that time. In addition, immediately after responding to the thermal sensation, the thermal comfort survey was answered on the same 5-point scale as the questionnaire used before the start of the experiment.

In this study, the EEG measurement device (B-Alert X10, Advanced Brain Monitoring, Carlsbad, CA, USA) was used. This device is used with three parts of the frontal lobe, F3, Fz, F4, and six regions of the parietal lobe, C3, Cz, C4, P3, POz, and P4. The occipital lobe responsible for visual stimulation and the temporal lobe responsible for auditory stimulation and memory recognition were excepted. The detailed location of measurement points is shown in Figure 2.

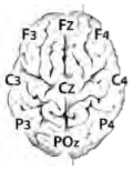

Figure 2. Electrode placements in the experiment

Before installation of the EEG device, the size of the head of the experiment participant was measured, and a strap suitable for the size was used. To facilitate the collection of electrical signals, a disposable sponge was attached to the electrode located on the strap, and then a water-soluble gel was applied. Also, when measuring EEG, a disposable electrode was attached to the mastoid as a reference electrode.

Meanwhile, for the accuracy of the electrical signal of the EEG, an Impedance test was conducted to check the resistance values on the scalp and electrodes before the start of the experiment. This experiment was started after the impedance value dropped below 30kΩ in a total of 9 sites and the signal stabilized. The EEG data was saved by a computer through a 1-40Hz pass filter, and one value was saved per second per 1Hz.

- *Experimental conditions*

Upward ramping experiment was conducted for a total of 70 minutes. In order to stabilize the physical condition of all participants equally, participants entered a pre-chamber with an air temperature of 25℃ and relative humidity of 50% and waited for 30 minutes. After entering the pre-chamber, the participant changed into experimental clothes, and the wireless EEG device was attached to the head. After the waiting period was over, the participant moved to the climate chamber and sat in the prepared seat. After a brief guide to the experiment and explaining how to use the questionnaire, the experiment was started and EEG measurements were conducted. The participant pressed the voting button at the moment he felt sensational change while staying in the climate chamber and questioned the thermal comfort at that time. Subsequently, the questionnaire was answered whenever the change in thermal sensation or thermal comfort was changed, and there was no limit to the number of responses.

In order to compare the EEG in the comfortable environment with the EEG at the moment of change to the uncomfortable environment, the indoor environment for 10 minutes after the start of the experiment maintained the initial condition. After that, the temperature and humidity were gradually changed so that participants could experience from a comfortable environment to a very uncomfortable environment.

- *Analysis*

For the questionnaire analysis, the responses of sensation and comfort were quantified. Thermal sensation was converted into Neutral (1), Slightly hot (2), Hot (3), and Very hot (4). Thermal comfort was quantified as Comfortable (1), Slightly comfortable (2), Slightly uncomfortable (3), Uncomfortable (4), and Very uncomfortable (5).

The removal of artifacts from the EEG data was carried out. The case where the data was not saved due to a large loss of EEG data or an operation error of the questionnaire response device was excluded. Finally, 246 data of 33 people (17 males and 16 females) were used for the analysis. In this experiment, the relative brain power value was calculated and used for the final analysis.

RESULTS

- *Thermal sensation and thermal comfort votes*

The average thermal sensation of the participants before the start of the experiment was 1.03, which was neither hot nor cold, and the average thermal comfort was 1.32, and they felt comfortable.

As shown in Figure 3, the results of examining the changes in the average thermal sensation and thermal comfort according to the gradual increase in temperature showed that the thermal sensation and thermal discomfort increased as time passed. The number of responses and response time varied. In the case of thermal sensation, participants felt 'slightly hot' from the beginning of the experiment. There was a temporal difference between thermal sensation and discomfort.

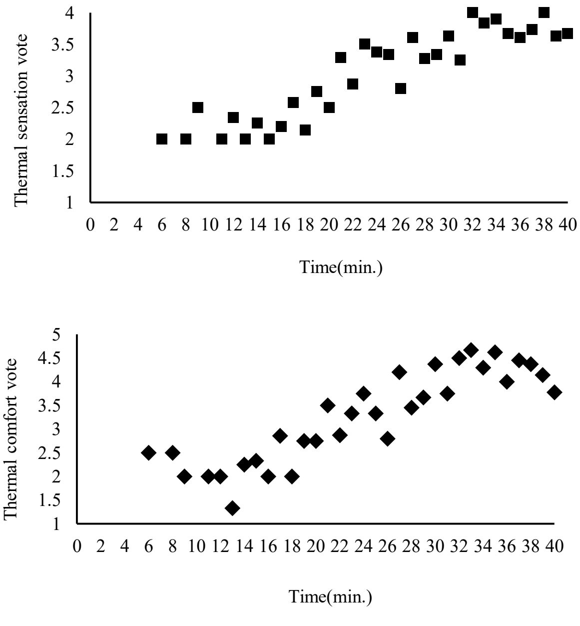

Figure 3. Time series of the thermal sensation vote and thermal comfort vote

- *Thermal discomfort and EEGs*

The results of examining the changes in EEG according to thermal comfort are as follows. The amount of change was calculated to eliminate individual baseline differences in EEG. The amount of EEG change was used by subtracting the average EEG for 2 minutes after the start of the experiment from the average EEG for 2 minutes after the participant responded to the questionnaire, and these values were expressed as Δrelative power. The EEG of the first voting with a change in thermal comfort was used in the analysis, and the case of repeated responses of the same response was excluded from the analysis. The analyzed sites were F3, Fz, F4, C3, Cz, C4, P3, POz, and P4, a total of nine sites (Fig.2).

The change in the relative power value of the brain waves according to the gradual temperature rise is as follows.

The change in relative alpha power according to the thermal comfort response is shown in Figure 4 and Figure 5. The change in relative alpha power of Cz and C3 sites tended to increase as it went from comfort to discomfort, and the items showing a statistically significant difference are as follows.

The amount of change in relative alpha power in the Cz region was significantly increased when participants felt “Slightly uncomfortable” and “Very uncomfortable” compared to when the participants felt “Comfortable”.

The amount of change in relative alpha power in the C3 area was significantly increased when participants felt that they were ‘Slightly uncomfortable’, ‘Uncomfortable’, and ‘Very uncomfortable’ compared to when the participants felt ‘Comfortable’.

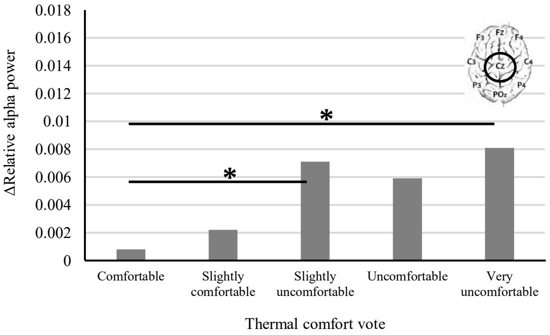

Figure 4. Relative alpha power change on thermal comfort vote at Cz

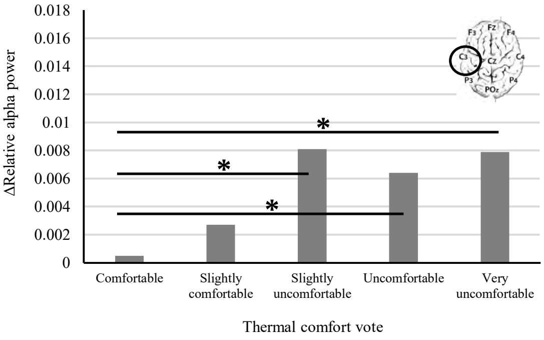

Figure 5. Relative alpha power change on thermal comfort vote at C3

The changes in the relative beta power according to the thermal comfort response are shown in Figures 6 ~ 8. The change in relative beta power of Fz, Cz, and C4 sites tended to increase as it goes from comfort to discomfort.

The amount of change in the relative beta power of the Fz, Cz, and C4 regions was significantly increased when the participants felt “Slightly uncomfortable” and very uncomfortable” than when they felt “Comfortable”.

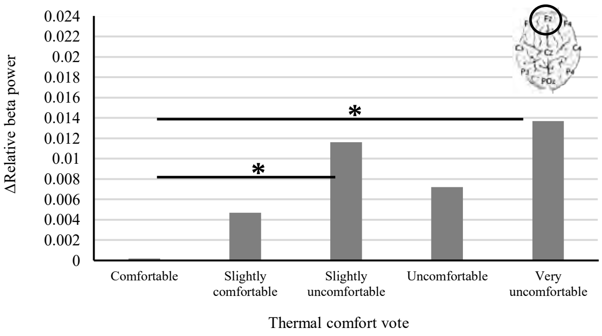

Figure 6. Relative beta power change on thermal comfort vote at Fz

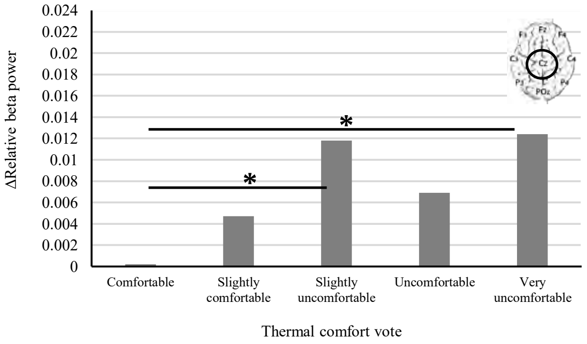

Figure 7. Relative beta power change on thermal comfort vote at Cz

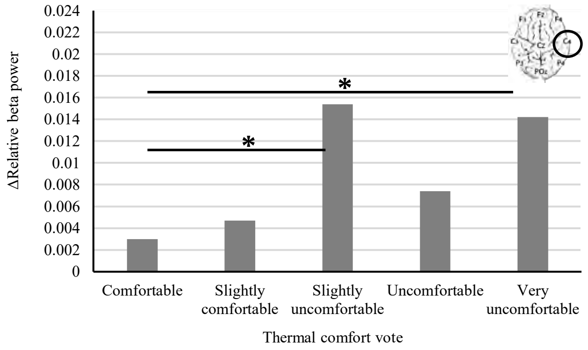

Figure 8. Relative beta power change on thermal comfort vote at C4

The change in relative gamma power according to the thermal comfort response is shown in Figure 9. The change in relative gamma power of the C3 site tended to increase as it went from comfort to discomfort. The amount of change in relative gamma power was also significantly increased when participants felt “Slightly uncomfortable” and “Very uncomfortable” than when they felt “Comfortable”.

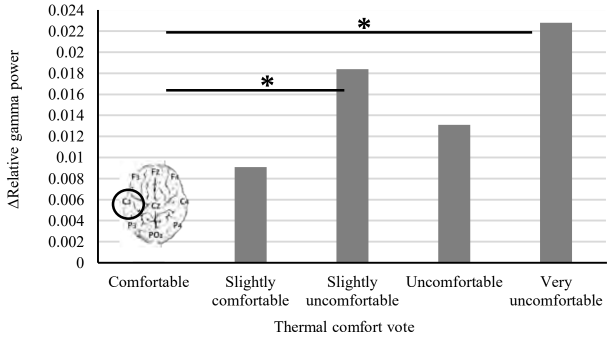

Figure 9. Relative gamma power change on thermal comfort vote at C3

DISCUSSION

This experiment was conducted to examine the expression of thermal discomfort and the change in EEG. In order to induce thermal discomfort, the air temperature was increased by 7 ℃ and the relative humidity was increased by 15% for 30 minutes to create a gradual change in the thermal environment. As a result, as time passed, that is, as the discomfort increased, the overall EEG increased. When examining the regions and frequencies of the EEG that were significantly increased, the alpha waves of Cz and C3, the beta waves of Fz, Cz and C4, and the gamma wave of C4 were increased.

In previous studies (Han & Chun, 2020), when the thermal displeasure was induced, the increase or decrease of a specific region and frequency was clear. However, in this experiment, EEG increased in all frequency bands. This means that, unlike thermal displeasure, where sudden changes caused instantaneous high arousal, the discomfort was expressed in a low arousal state because of gradual changes, and the EEG changes with a mechanism different from displeasure.

n=13

In a study that examined changes in EEG on the effects of various emotions through acoustic stimulation, a previous study in which the overall frequency band of the EEG was higher when negative emotions were compared to positive emotions (Kao et al, 2015).

In other words, the change of EEG according to the thermal comfort response was significantly increased, but there was no difference in EEG for each frequency and the overall EEG increased. This experiment was conducted only under the condition of increasing the temperature, but in a future study, it is planned to investigate how the EEG changes when the temperature is lowered and the thermal discomfort caused by the cold is felt. Therefore, in future studies, based on the results of this study and later experiments, the relationship between thermal discomfort and EEG can be more clearly investigated, and a thermal comfort model that considers EEG parameters can be developed.

CONCLUSIONS

This study was to find the EEG region and frequency band that can represent the discomfort of the occupants by checking the changes in EEG due to thermal discomfort.

As a result of examining the changes in EEG according to thermal discomfort, when discomfort due to heat was expressed, the alpha waves of Cz and C3 increased, the beta waves of Fz, Cz, and C4 increased, and the gamma wave of C4 was increased.

This study investigated only the discomfort according to the gradual temperature change and the response of the brainwaves accordingly, but in the future, it will be possible to expand the area to not only the thermal environment but also other indoor environments and will contribute to providing a comfortable indoor environment.

ACKNOWLEDGMENTS

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