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Analysis of the Correlation between Thermal Sensations and Brain Waves via EEG Measurements

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Abstract

In this study, the thermal comfort of heated seats in automobiles was analyzed by correlating EEG (electroencephalogra m) to thermal sensations. During the subjective evaluation of the satisfaction of the heated seat, it was found that the optimal temperature of the seat was 40–50 ℃ while the outdoor temperature was -20 ℃, and that the higher the deviation between the seat and the outdoor temperatures, the lower the thermal sensation satisfaction. Furthermore, relative beta wave (RB; β/brain wave sum) and alpha-beta wave ratio (RAB; α/β) were found to be effective indexes for brain waves. RAB increased and RB decreased with thermal sensation satisfaction, which depended on the temperature of the seat. However, only RAB showed a significant correlation to thermal sensation satisfaction within the temperature deviation of the heated seat, and RAB was high when the temperature deviation of the heated seat was small.

Keywords: Heating mat, EEG measurement, thermal sensations, Analysis of the correlation , brain waves

INTRODUCTION

Because automobile seats affect passenger comfort, the effective design of these seats is important. For this reason, automobile seats are being designed to be comfortable, stable, and convenient. Recently, automobile seat comfort has become more important, and many studies evaluating automobile seat satisfaction have been conducted. Through a subjective assessment, Wachsler and Learner (1960) found that the comfort of the back and hip areas was highly correlated to the overall comfort of the automobile seat. Smith et al. (2006) developed a statistically reliable comfort questionnaire. However, conventional evaluation methods for seat comfort primarily involve subjective questionnaires that aim to measure the driver's comfort to determine what affects the comfort of the seat itself. Recently, electrophysiology has been developed to objectively quantify pleasant/unpleasant stimulations via brain waves (EEGs).

In this study, the correlation between thermal sensation and brain waves (as a proxy for comfort of the heated seat temperature and ambient temperature) was analyzed using biomedical signal measurements and subjective surveys.

EXPERIMENTAL SET-UP

Measurement System Configuration

For the experiment, the indoor environment was maintained at 20 ℃ using a humidity chamber to mimic winter conditions. A heating wire was designed to adjust the temperature of the seat, and the seat surface temperature was maintained using the seat heating controller. The participant, after changing into standard experimental dress, was stabilized for 30 min in a humidity chamber by wearing an EEG cap with brain wave measurement equipment.

A survey of the initial conditions of the participant was taken before the participant entered the humidity chamber and sat on the heated seat. Brain wave measurement began when the participant was fully seated and the brain wave signal stabilized. The EEG signal was recorded for one minute, after which the participant exited the chamber and answered the satisfaction survey. Fig. 1 shows the configuration of the measurement system of this experiment.

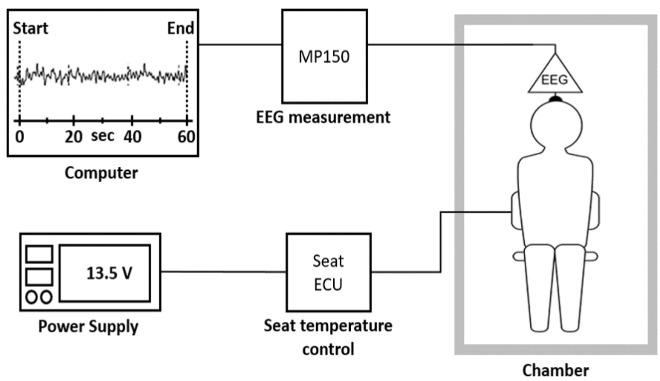

Figure 1 : Thermal comfort test system for thermal comfort tests

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Survey

The survey used in the study has been used in many studies to measure satisfaction, and a subjective evaluation questionnaire was prepared for before and after the experiment to correlate to brain wave measurements. Before the experiment, participants checked the degree of tension and stability in the indoor environment. After the experiment, the thermal comfort of the automobile and the satisfaction of the heated seat were measured to the first decimal point using a 5-point scale.

Seat Temperature

Seat temperature is the most important experimental factor in this study, and its value was set as 40 ℃, which is close to the average body temperature (36.5 ℃). The temperature range was 40 ± 10 ℃ with heat settings at 30 ℃, 40 ℃, and 50 ℃. The experiment was performed by deviating the seat temperature as -20 °C, -10 °C, and 0 °C relative to the reference temperature.

The heated seat was designed using a heat line pattern on the left and right sides of an existing seat, under the leather cover of the seat. NTC thermistors were attached to the left and right surfaces of the seat so that the right and left hot wires could be maintained at the desired temperature. The temperature of the vehicle seat was designed to be maintained from 10–50 ℃ using the NTCs. Measured samples are shown in Fig. 2, and Table 1 lists the temperatures for the heated seat in this study.

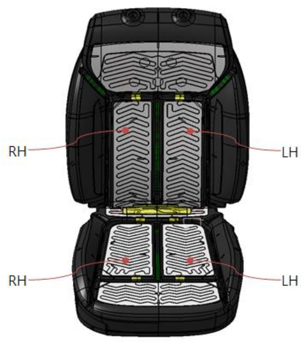

Figure 2 : Thermal seat structure for vehicle

Table 1 : Thermal comfort measurement temperature variables

Seat	Tmax=30℃	Tmax=40℃	Tmax=50℃
Environment	LH / RH	LH / RH	LH / RH
-20℃	30 / 30	40 / 40	50 / 50
	30 / 20	40 / 30	50 / 40
	30 / 10	40 / 20	50 / 30

Brain Wave Measurement

Participants for this study were 10 mentally healthy male college students with no neuropsychiatric history, such as those of brain trauma, attention deficit disorder, or problems related to normal body conditions. Individuals with neuropsychiatric conditions were excluded from the experiment to minimize experimental error. Drugs that could affect the experiment, such as caffeine and alcohol, were prohibited for consumption 24 h before the experiment.

All participants wore the same garments for the experiment. The attire was based on standard winter clothing (underwear, T-shirt, long-sleeved shirt, winter coveralls, cotton pants, socks, and sneakers). Table 2 shows that the insulation index of the experiment clothing was 1.49 Clo, which was measured as per the recommendations of ASHRAE 55-2004.

Table 2: Thermal insulation index for thermal seat testing

Cloting	Cloting included	I_{cl} (clo)	$m^2 \cdot °C/W$
Underwear	Panties	0.03	0.0046
	T-shirt	0.08	0.0124
Footwear	Calf-length socks	0.03	0.0046
	Shoes	0.02	0.0031
Shirts	Long-sleeve flannel shirt	0.34	0.0527
Shirts and Blouses	Straight trousers	0.24	0.0372
	Coveralls	0.48	0.0744
Total		1.49	0.2309

A brain wave measurement device was installed to measure the change of the physiological signals under different seat temperatures. Brain waves were measured using the 10–20 International Electrode Arrangement, as shown in Fig.3, with electrodes attached to the left and right frontal lobe (Fp1, Fp2), frontal lobe (F3, F4), parietal lobe (P3, P4), and occipital lobe (O2, O2). Ground electrodes were attached to both earlobes (A1, A2) to establish the baseline signal, thereby increasing the accuracy of the brain waves. Measurement was performed using a Biopac MP150 and stored in a computer using a sampling frequency of 2000 Hz and 16-bit AD conversion. The brain wave measurement system is shown in Photo 1 and the electrode positions are shown in Figure 3.

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Photo 1: EEG measurement photograph

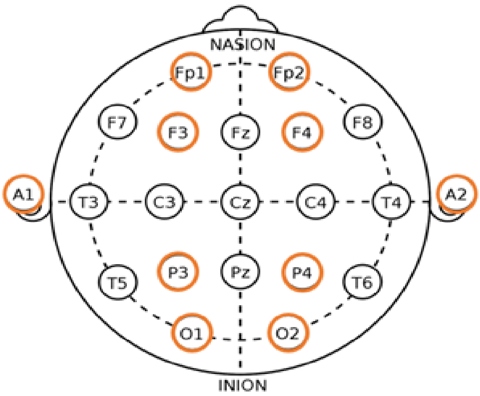

Figure 3: EEG electrode position

EXPERIMENTAL RESULTS

Survey Result Analysis

After the experiment, the thermal sensation satisfaction was analyzed to verify the thermal comfort of the seat. The observations were verified using the five-point scale for seat satisfaction using a subjective questionnaire. The heated seat showed high thermal comfort when the temperature was 40–50 °C, which is 10 °C higher than the body temperature. Figure 4 shows the results of the survey.

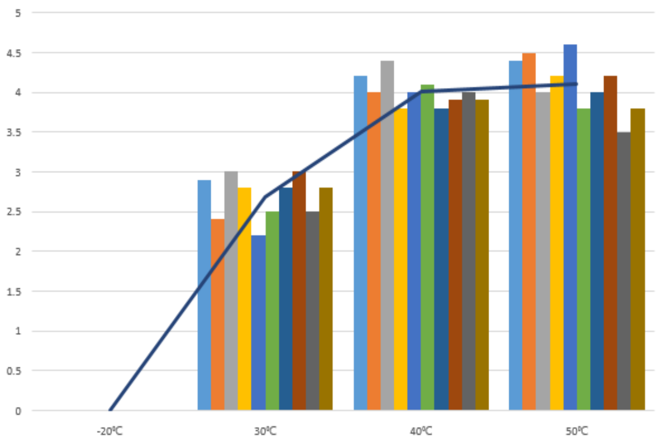

Figure 4 : Results of subjective survey by heated seat(Temp)

Moreover, the survey showed that higher thermal comfort without heated seat temperature deviation between the left and the right as indicated that the highest satisfaction was observed when the temperature and temperature distribution of the seat were uniform. Figure 5 shows the results of the survey.

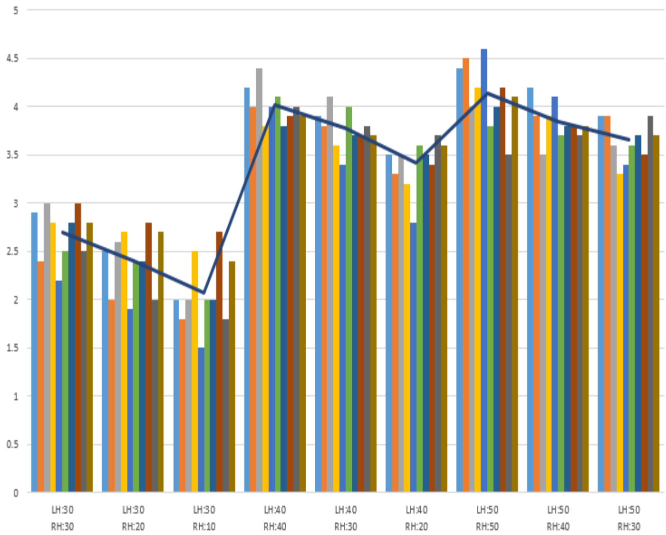

Figure 5: Results of subjective survey by heated seat (Temp deviation)

Brain Wave Measurement Results

After brain wave measurement, an IIR filter was used to remove periodic noise and frequencies outside of the brain wave region. The frequency required to analyze brain waves is the value of the potential signal of the brain surface, which is between 0.5–40 Hz. The data measured outside that range is unnecessary for analysis, and frequency components from 0–0.5 Hz and > 40 Hz were removed using a bandpass filter. Figure 6 shows the data obtained by amplifying the brain wave signals 50000 times and recording at a sampling rate of 1000 Hz. Figure 7 shows the frequency before and after frequency filtering, where red is the data before filtering, and blue is the data after filtering.

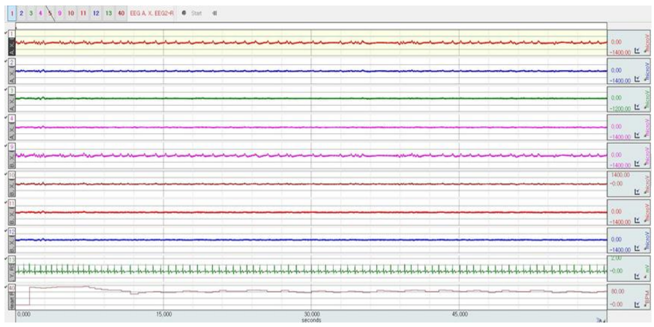

Figure 6: EEG measuring electrode waveform

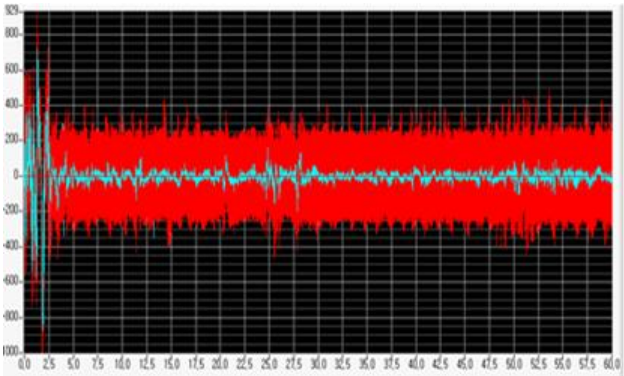

Figure 7: Noise rejection filtering

Brain waves measured with time must be converted to the frequency domain to separate and analyze the specific frequency domain signals. A digital filter is used to display frequencies in the desired range in the time domain. In this study, the 55th order Bessel filter was used as the IIR filter to divide the alpha (α), beta (β), delta (δ), and theta (θ) waves to read the brain waves.

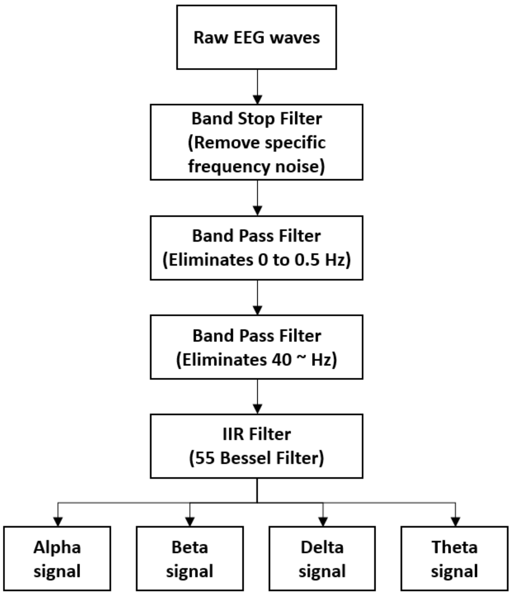

Figure 8: EEG Procesing Flowchart

The overall schematic of the algorithm is shown in Fig. 8, and the algorithm is as follows. After brain wave measurement, to confirm that the brain wave signal could appropriately evaluate thermal comfort, the correlations between alpha, beta, delta, and theta waves were analyzed using the mean absolute power of the brain wave frequency spectrum as well as the relative power ratio of the brain wave frequency spectrum to the brain wave sum(B.S). Eq. (3.1) was used to calculate the relative power(R.P) ratio for the brain wave sum, and Eq. (3.2) was used to calculate the power of all brain activity.

$$R.P = \frac{x_{power}}{\alpha_{power} + \beta_{power} + \delta_{power} + \theta_{power}} \quad \text{Eq.(3.1)}$$

$$(x = \alpha, \beta, \delta, \theta)$$

$$B.S = \alpha_{power} + \beta_{power} + \delta_{power} + \theta_{power} \quad \text{Eq.(3.2)}$$

Table 3 shows the correlation of each brain wave index to the thermal comfort survey results of all participants. β is valid at a level of significance of 0.01 because correlation analysis was based on the absolute value of the brain wave; however, the correlation between them was low (-0.328). The relative power ratio brain wave spectrum for the brain wave sum showed an effective range at the 0.05-level, overall. Because the absolute value of each participant's brain waves is different, analysis of the brain wave of multiple participants can yield meaningful results when using the relative brain wave ratio. A significant positive correlation coefficient of 0.4 or higher was found for the relative beta wave (RB; β/brain wave sum) and the alpha-beta wave ratio (RAB; α/β), showing significant correlations for RB and RAB.

Table 3: Overall correlated analysis results by brain wave index

index	Correlation	p
AD	0.101	0.419
AT	0.095	0.447
AA	0.001	0.994
AB	-0.328	0.007
RD	0.321	0.009
RT	0.373	0.001
RA	0.252	0.041
RB	-0.497	0.001
RAB	0.516	0.001
SEF50	-0.109	0.384

Correlation analysis between survey and brain waves

Seat temperature

Relative β (RB) Waves

Table 4 demonstrates the correlation of mean RB of the participant per experimental case. Participants A–H had correlation coefficients of 0.7 or higher, and Participant J had a correlation coefficient of 0.6. This shows that RB strongly influences the thermal comfort for localized heat.

Table 4: Beta wave for seat temperature

Division	-20℃	30℃	40℃	50℃	Correlation	p
Part. A	0.601	0.596	0.505	0.399	-0.752	0.025
Part. B	0.669	0.488	0.437	0.471	-0.931	0.069
Part. C	0.712	0.516	0.474	0.456	-0.986	0.014
Part. D	0.545	0.437	0.467	0.476	-0.770	0.230
Part. E	0.635	0.527	0.554	0.534	-0.789	0.221
Part. F	0.610	0.505	0.443	0.439	-0.996	0.004
Part. G	0.576	0.552	0.318	0.386	-0.799	0.201
Part. H	0.624	0.512	0.457	0.355	-0.924	0.076
Part. I	0.568	0.551	0.569	0.557	-0.194	0.806
Part. J	0.604	0.601	0.528	0.357	-0.666	0.334

Relative α/β (RAB) Waves

Table 5 lists the correlation of the mean RAB waves of the participant per experimental case. Participants A, B, C, E, F, G, H, and I had correlation coefficients of 0.7 or higher, and Participant D had a correlation coefficient of 0.4. This shows that RAB waves are strongly correlated to the thermal comfort of heated seats.

Table 5: α/β wave for seat temperature

Division	-20℃	30℃	40℃	50℃	Correlation	p
Part. A	0.079	0.118	0.117	0.154	0.884	0.116
Part. B	0.130	0.164	0.179	0.194	0.992	0.008
Part. C	0.123	0.181	0.201	0.245	0.893	0.107
Part. D	0.164	0.196	0.204	0.164	0.401	0.599
Part. E	0.117	0.132	0.151	0.169	0.963	0.037
Part. F	0.081	0.093	0.115	0.098	0.889	0.111
Part. G	0.141	0.159	0.180	0.227	0.793	0.207
Part. H	0.136	0.151	0.172	0.217	0.783	0.217
Part. I	0.129	0.149	0.202	0.169	0.898	0.102
Part. J	0.098	0.130	0.144	0.151	0.995	0.005

Seat temperature deviation

Relative β (RB) Waves

Table 6 shows the correlations of the mean RB wave of the participants for each case in the seat temperature deviation experiment. A negative correlation of 0.4 or greater was noted for all participants except Participants B, D, G, and I.

Table 6: Beta wave for seat temperature deviation

LH/RH (℃)	Part.A	Part.B	Part.C	Part. D	Part.E	Part.F	Part. G	Part.H	Part. I	Part. J
30/30	0.60	0.49	0.52	0.44	0.53	0.51	0.55	0.51	0.55	0.60
30/20	0.49	0.52	0.64	0.63	0.58	0.52	0.53	0.66	0.63	0.62
30/10	0.61	0.59	0.67	0.48	0.58	0.51	0.46	0.55	0.47	0.65
40/40	0.51	0.44	0.47	0.47	0.55	0.44	0.32	0.46	0.57	0.53
40/30	0.55	0.58	0.57	0.56	0.58	0.43	0.61	0.50	0.56	0.55

LH/RH (°C)	Part.A	Part.B	Part.C	Part. D	Part.E	Part.F	Part. G	Part.H	Part. I	Part. J
40/20	0.55	0.52	0.49	0.60	0.57	0.50	0.48	0.57	0.63	0.57
50/50	0.40	0.47	0.46	0.48	0.53	0.44	0.39	0.35	0.56	0.36
50/40	0.54	0.59	0.41	0.58	0.47	0.53	0.56	0.45	0.57	0.61
50/30	0.49	0.51	0.57	0.55	0.50	0.46	0.43	0.56	0.43	0.54
Correlation	-0.59	-0.30	-0.68	-0.07	-0.49	-0.66	-0.25	-0.82	0.01	-0.72
P	0.09	0.43	0.04	0.85	0.18	0.05	0.52	0.01	0.97	0.03

Relative αβ (RAB) Waves

Table 7 shows the correlations of the mean RAB wave of the participants for each case of the experiment. All ten participants had positive correlations of 0.4 or greater, confirming that RAB waves are related to thermal comfort for local thermal deviations. Regarding satisfaction of seat temperature deviation, for all participants except Participants F and G, RAB wave was high when there was no temperature deviation and low when there was a temperature deviation, which was shown by the significant brain wave change when there was a temperature deviation.

Table 7 : α/β wave for seat temperature deviation

LH/RH (°C)	Part. A	Part. B	Part. C	Part. D	Part. E	Part. F	Part. G	Part. H	Part. I
30/30	0.12	0.16	0.18	0.20	0.13	0.09	0.16	0.15	0.15
30/20	0.13	0.17	0.15	0.12	0.13	0.08	0.16	0.16	0.13
30/10	0.09	0.15	0.12	0.15	0.15	0.08	0.16	0.15	0.18
40/40	0.12	0.18	0.20	0.20	0.15	0.11	0.18	0.17	0.20
40/30	0.11	0.19	0.16	0.19	0.13	0.12	0.16	0.22	0.17
40/20	0.12	0.14	0.17	0.18	0.13	0.10	0.19	0.16	0.18
50/50	0.15	0.19	0.24	0.16	0.17	0.10	0.23	0.22	0.17
50/40	0.14	0.18	0.20	0.17	0.17	0.10	0.18	0.18	0.18
50/30	0.10	0.18	0.19	0.16	0.16	0.12	0.19	0.20	0.19
Correlation	0.52	0.69	0.69	0.44	0.67	0.81	0.66	0.74	0.70
p	0.15	0.04	0.04	0.24	0.05	0.01	0.06	0.02	0.04

As described above, RB and RAB were found to correlate significantly with the thermal comfort of the seat. Thermal discomfort analysis of the temperature deviation showed a significant correlation with only RAB. Table 8 summarizes the correlation between seat temperature, seat temperature deviation to the ambient temperature, and EEG signals.

Table 8 : EEG Correlation for Heat Seats

Division	reference temperature	Relative β (RB) Waves	Relative αβ (RAB) Waves
Seat Temperature Comfort	30℃	correlation	correlation
	40℃	correlation	correlation
	50℃	correlation	correlation
Seat Temperature Deviation Discomfort	30℃	correlation	correlation
	40℃	correlation	correlation
	50℃	correlation	correlation

CONCLUSIONS

In this study, subjective surveys and brain wave measurements (EEGs) were performed for different operating temperatures for heated seats during the winter, and the correlation between thermal sensation and biomedical signals was analyzed. The subjective satisfaction surveys found that the optimal heating temperature was approximately 40–50 ℃ at an outdoor temperature of -20 ℃ and that the higher the thermal seat thermal deviated from the outdoor temperature, the lower was the thermal sensation satisfaction.

RB and RAB were found to be effective indices for analyzing the brain wave spectrum for the heated seat. RAB increased and RB decreased with thermal sensation satisfaction depending on the temperature of the seat. However, the thermal sensation satisfaction in the temperature deviation of the heated seat showed a significant correlation only with the RAB index, and was found to be the highest when the temperature deviation of the heated seat was narrow.

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