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# Evaluation of comfort in subway stations via electroencephalography measurements in field experiments

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ABSTRACT

There is a growing body of research on the relationship between electroencephalography (EEG) and human comfort evaluation. However, most of these studies have addressed this relationship in a laboratory environment. In this study, we investigated the correlation between comfort level and brainwaves in a real-world environment. Field experiments were performed at two subway stations, a comfortable station and an uncomfortable station, to measure and compare the EEGs of 30 healthy students. The EEG signal patterns showed that the beta and gamma band powers were higher at the uncomfortable station than at the comfortable station. However, unlike previous studies where significant gamma bands activity was not observed, significantly high gamma band activity was observed in uncomfortable field environments in this study. In addition, in contrast to the results of previous studies, the alpha band activity did not increase in the comfortable field environment in this study. The present study shows that brainwave measurements can be used as an additional method to observe the responses of a participant in field environments that do not appear in laboratory experiments.

## 1. Introduction

In recent years, the field of neuropsychology has attracted increasing research attention, resulting in an increasing number of applications being studied. Several studies have used electroencephalography (EEG) in indoor environmental comfort-related research. EEG can be used to measure an electrical physiological signal that occurs in the region of the brain that controls emotional responses. The use of EEG with traditional questionnaires have allowed researchers to analyze a participant's psychological state or comfort evaluation mechanism by various environmental changes [1–4].

Several studies have used EEG in comfort-related research. Yao et al. examined the brainwave power of participants at different frequencies by varying the ambient temperature in a laboratory environment to generate different thermal comfort levels. Experimental results indicated that the theta, delta, alpha, and beta band powers changed significantly with variations in the thermal environment. In particular, the proportion of beta waves was inversely proportional to the thermal comfort level. In addition, the proportion of alpha waves was highest in a slightly cool thermal environment and decreased in an uncomfortable thermal environment [1]. Kang et al. quantified the differences in participants' alpha wave proportions in response to the type of air current blowout from an air conditioner during cooling (natural or artificial wind). The results demonstrated that the proportion of alpha waves was higher for cooling with natural wind than with artificial wind [3].

Previous studies have also investigated brainwaves in different visual or aural environments. Noguchi observed the influence of a combination of two color temperatures (3000 and 5000 K) and two illuminance levels (30 and 150 lx) on the EEG signals of participants with lower physiological activity [4]. Akita et al. observed brainwaves and confirmed a variance in the perception level of sound stimuli when performing a task while exposed to different ambient sound levels (33, 40, 50, and 70 dBA) [5].

These studies on the correlations between brainwaves and comfort levels have predominantly been conducted in laboratory environments because it is easier to control variables, and most brainwave measurement equipment requires connections to larger equipment in a laboratory. However, recent developments in Bluetooth-based wireless brainwave measurement equipment have enabled brainwave measurements to be conducted in real-world field experiments. In addition, in order to practically apply laboratory measurement results, onsite measurement data from real-world environments is needed.

In addition, the possibility of EEG measurements in field evaluations presents important implications. Brain science, which measures

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biological signals in frequency bands per second in real-time, is an appropriate approach to create big data for individual reactions to various factors. A big data and real-time processing technology are needed for future HVAC system. However, to date, few studies have measured EEG activity in a field environment.

To confirm whether the results of laboratory experiments can be reproduced in the field, and in the future, it is the basic work for the data driven approach using big data based on brain science in the field, we measured the brainwaves of participants in a real-world environment.

Further, most published studies on the correlations between EEG signals and comfort levels have examined responses to a single stimulus such as temperature, air currents, ambient sound, or color. However, unlike the controlled conditions present in a laboratory, it is impossible to separate one stimulus from the diverse range of simultaneous stimuli present in real-world environments. In other words, it is impossible to conduct a field experiment involving a single variable. Therefore, in this study, comfort was defined as overall comfort in the presence of complex environmental stimuli such as temperature, ambient sound, air currents, and light.

The purpose of this study is to investigate tendency of EEG activity related to comfort in field experiments and compare the result of this study with the tendency of EEG activity in previous study conducted in laboratory environment For this purpose, we conducted two experiments, one in a comfortable subway station and one in an uncomfortable subway station. Two subway station platform with same function were selected as two field environment to control participants' expectation. Two field environment were verified as environment with different comfort levels from a previous study [6].

## 2. Methods

The experiment was designed to measure the participants' EEG signals in indoor environments with different associated comfort levels. The following factors were considered in selecting the experimental sites: (1) the two environments had to have similar functions and visual structures to ensure that participants had similar expectations for their comfort levels, and (2) the two environments had to show quantitatively verifiable differences in occupant comfort levels.

Accordingly, the experimental sites were selected based on a previous study that surveyed subway passenger comfort levels in six different subway stations in Seoul, Korea [6]. The subway platform that was assessed as the most comfortable was selected as a "relatively comfortable station" and is hereafter referred to as "Platform 1." Another subway platform that was assessed as the most uncomfortable was selected as a "relatively uncomfortable station" and is hereafter referred to as "Platform 2."

To confirm that Platforms 1 and 2 were contrasting environments in terms of comfort, indoor environmental quality was measured simultaneously during this experiment via environmental measurement equipment. The measurement equipment measured air temperature, air velocity, and relative humidity, and contained a 150-mm black bulb thermometer (HD29371, Delta OHM; Padova, Italy), illuminance sensor (HD 2021T, Delta OHM; Padova, Italy), and sound level meter (TES-53H, TES; Taipei, Taiwan). Table 1 shows the environmental measurement results of the two platforms. These results were compared using the *t*-test, which showed that Platform 2 was significantly colder, darker, and noisier than Platform 1 ($p < 0.001$).

Additionally, the participants in this study also evaluated their subjective comfort level, which confirmed the results of a previous study by Han et al. [6]. The participants assessed comfort using a five-point scale (1, very uncomfortable; 2, uncomfortable; 3, neutral; 4, comfortable; 5, very comfortable) after EEG measurements were taken. The evaluation results shown in Fig. 1 indicate that Platform 2 was less comfortable than Platform 1, which was consistent with the previous survey.

**Table 1**
Physical properties of a comfortable subway platform (Platform 1) and an uncomfortable subway platform (Platform 2).

| | Platform 1 | Platform 2 | *t* |
|---|---|---|---|
| Air temperature | 17.6 ± 0.4 °C | 11.8 ± 1.5 °C | −123.449*** |
| Global temperature | 21.1 ± 0.3 °C | 15.4 ± 1.1 °C | −161.997*** |
| Humidity | 30.7 ± 1.3% | 27.7 ± 2.9% | −29.558*** |
| Illumination | 204.9 ± 7.1 lux | 178.0 ± 2.7 lux | −114.815*** |
| Noise level | 61.2 ± 5.1 dB(A) | 64.4 ± 2.2 dB(A) | 18.361*** |
| Air movement | 0.1 ± 0.1 m/s | 0.3 ± 0.2 m/s | 25.139*** |

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

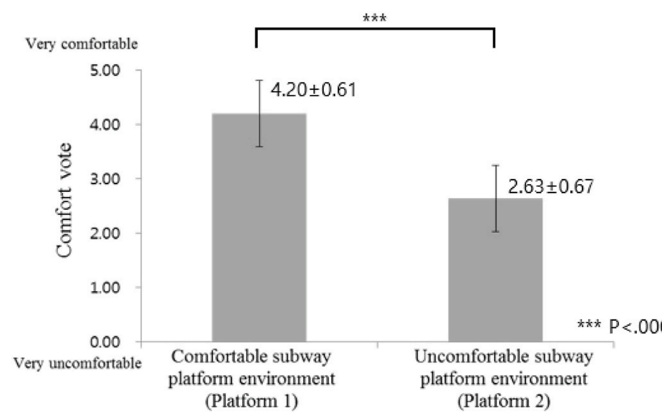


**Fig. 1.** Comfort assessment of a comfortable subway platform (Platform 1) and an uncomfortable subway platform (Platform 2). Error bars show the mean and standard deviation.

### 2.1. Data collection and processing

The participants included 30 healthy university students who were 20–30 years of age. All participants experienced the two contrasting environments while sitting on a bench. However, the participants were not exposed to both environments one after the other because the two stations were not close enough for participants to move from one to the other in a single day. Instead, an experiment was conducted at Platform 1 one week after the first experiment was conducted at Platform 2, under the premise that one week was sufficient to attenuate the effect of exposure to the first test environment.

The participants wore a Bluetooth-based wireless EEG device (B-Alert X10, ABM; CA, USA). This device was attached by nine electrodes to points on the scalp across the frontal and parietal regions (Fig. 2), and two referential electrodes were attached to the mastoids.

After connecting the EEG device, the participants wore thin hoods to hide the device from other passengers (Fig. 3).

Participants sat on a bench in the experimental environment, and a

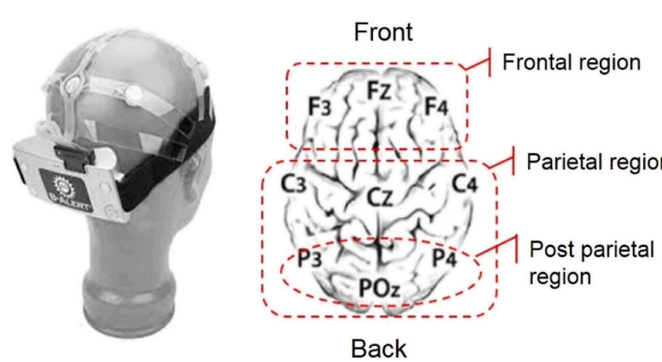


**Fig. 2.** Electroencephalography device (left) and electrode attachment points (right).

**Fig. 3.** Electroencephalography measurements in a comfortable subway platform environment (Platform 1, left) and an uncomfortable subway platform environment (Platform 2, right).

researcher performed an impedance level test to assess the resistance between the scalp and the electrodes. Once the impedance levels of the nine electrodes were below 40 Ω and the EEG signal had stabilized, EEG data was collected for 5 min. The researcher was 5 m away from the seated participant and received EEG data via Bluetooth from the connected EEG device.

EEG time series data were computed into an absolute EEG power according to the frequency band for every second via a fast Fourier transform (FFT) using a software package (B-Alert Live, ABM; CA, USA). In this study, the absolute EEG powers were classified by the following five frequency bands that are generally applied in brain wave studies: delta band (1–3 Hz), theta band (3–7 Hz), alpha band (8–13 Hz), beta band (13–30 Hz), and gamma band (25–40 Hz) [7,8].

However, some of the data was contaminated by four artifacts: spikes, saturation, excursions, and electromyogram. Data that were contaminated by more than 50% were deleted from the analysis. Finally, EEG data from 13 participants were selected as data samples for the analysis. Only artifact-free EEG data were used to ensure the reliability of the analysis results.

### 2.2. Statistical analysis

A repeated measures (RM) multivariate analysis of variance (MANOVA) was performed to determine whether the EEG powers were affected by the differences between the two environments. The environmental variables (two environments that contrasted in terms of comfort) and the measurement point variable (nine points on the scalp) were set as independent variables. The linear combination of EEG powers of five frequency bands was designed as a dependent variable of RM MANOVA.

After determining the effects of environment factors on the EEG power by RA MANOVA, a RM analysis of variance (ANOVA) was performed to analyze the effects of the environment on the EEG power at each frequency band. Similar to the RM MANOVA, the environment variables and the measurement point variable were set as independent variables. However, the EEG powers of each frequency band was set as dependent variables, and the statistics were conducted separately at each frequency band. The Greenhouse-Geisser method was adopted to control a violation of the sphericity assumption.

## 3. Results

Table 2 shows that the interaction between the environment and the measured factors was statistically significant when two-way RM MANOVA was performed on the powers of the five frequency bands measured on Platforms 1 and 2. The F-value indicates the scale of the difference of the variance between the means of the two groups (F = variation between sample means/variation within the samples). The p-value was calculated using the F-value from the F-distribution, which indicated

**Table 2**
Interaction between the environmental factors and the measurement site as a result of three-way repeated measures multivariate analysis of variance for electroencephalography power measured in a relatively comfortable platform environment and an uncomfortable platform environment.

| | *Value* | *F* | *Df* | P | $\eta\rho^2$ |
|---|---|---|---|---|---|
| Pillai's Trace | 0.579 | 1.573* | 40 | 0.016 | 0.116 |
| Wilks's Lambda | 0.518 | 1.644** | 40 | 0.010 | 0.123 |

**: $p < 0.01$, *: $p < 0.05$ df, degrees of freedom.

how significantly different the means of the groups were. The partial $\rho^2$ ($\eta\rho^2$) represents the proportion of variability in the dependent variables due to the independent variables. The $\eta\rho^2$ values shown in Table 2 represents the size of the interaction between the environmental factors and the measurement site on EEG power.

A statistically significant interaction between the environment and the brainwave band power indicated that the differences in the subway platform environments significantly affected brainwave power.

The analysis results indicating whether environmental factors had a statistically significant influence on brainwave band power are shown in Table 3. The results showed that the main effects of the environment on beta and gamma wave power were statistically significant.

Fig. 4 shows this result in graphs of power distribution for beta and gamma waves associated with environmental factors and electrode positions (see Fig. 2 for electrode positions). The comparative power difference between the two environments was larger for beta and gamma waves. In addition, the lines representing the two experimental environments in the graph were parallel for all electrode positions, indicating that environmental factors had a similar impact at all 9 EEG electrode locations.

## 4. Discussion

The primary aim of the present study was to investigate the differences in the brain activity of participants in contrasting environments by evaluating EEG signals individual frequency bands. A comparison of the

**Table 3**
Six main effects of the environment on electroencephalography power in each frequency band measured within a comfortable subway platform environment and an uncomfortable subway platform environment.

| | SS | *Df* | MS | F | P | $\eta\rho^2$ |
|---|---|---|---|---|---|---|
| Delta | 0.023 | 1 | 0.023 | 1.135 | 0.308 | 0.086 |
| Theta | 0.022 | 1 | 0.022 | 1.787 | 0.206 | 0.130 |
| Alpha | 0.004 | 1 | 0.004 | 0.135 | 0.720 | 0.011 |
| Beta | 0.376 | 1 | 0.376 | **7.617*** | 0.017 | 0.388 |
| Gamma | 1.070 | 1 | 1.070 | **5.737*** | 0.034 | 0.323 |

*: $p < 0.05$ SS, sum-of-squares; df, degrees of freedom; MS, mean squares.

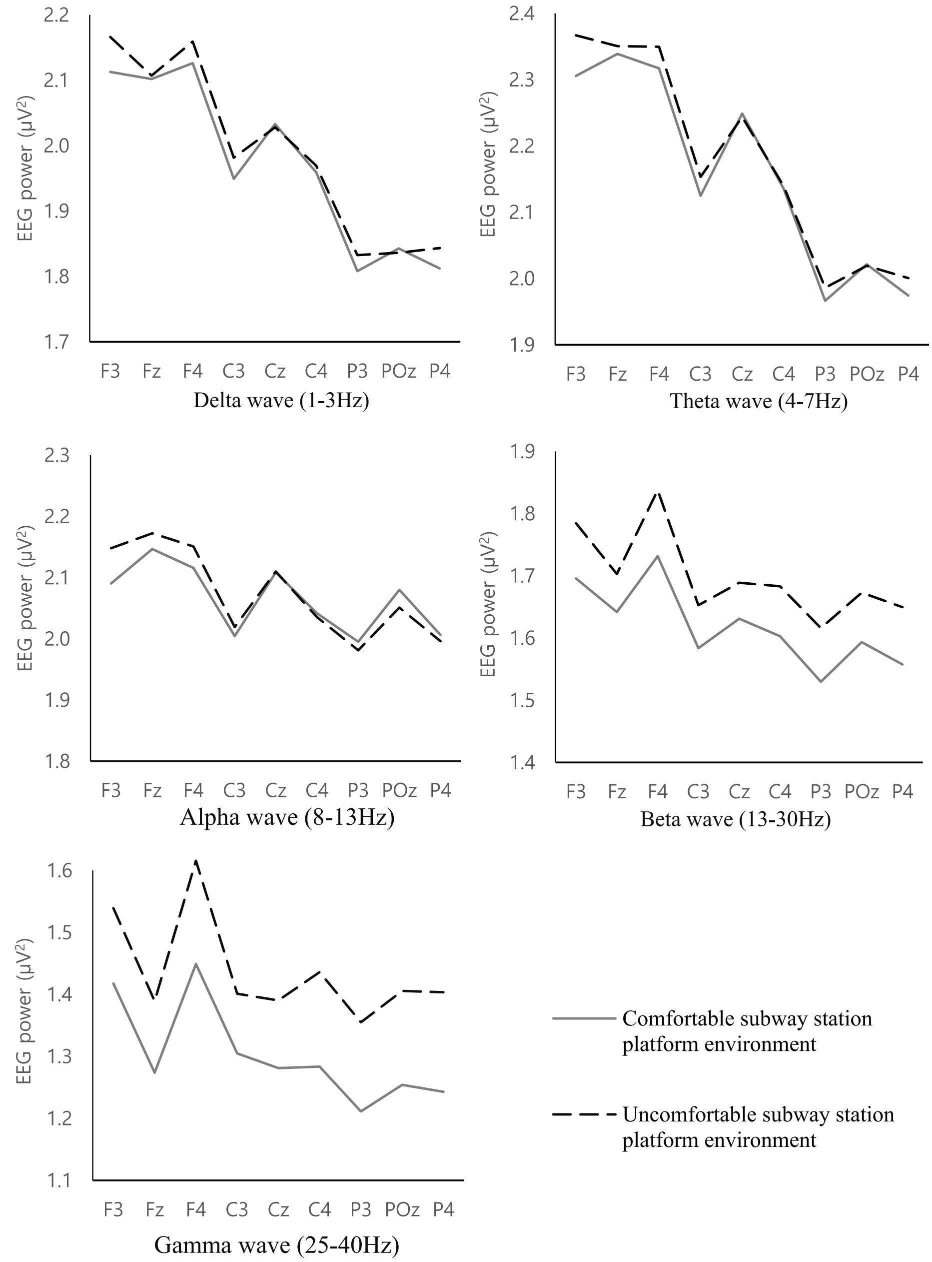


**Fig. 4.** Distribution of electroencephalography (EEG) power measured within a comfortable subway platform environment and an uncomfortable subway platform environment.

EEG activity measured at the comfortable and uncomfortable subway platforms showed a significant difference in the beta and gamma bands with an associated significance level of 0.05.

Beta bands of EEG signals are known to be associated with arousal, strained state, active thinking and active attention [9]. In addition, they are known to have high responses to stimuli that cause negative emotions [10,11]. In an indoor environment, Yao et al. showed that the EEG power of beta bands (14–35 Hz) was dominant in a chamber environment with ambient temperature 21 °C and 29 °C compared to that at 24 °C and 26 °C, and the EEG power of beta bands was increased as the degree of uncomfortable thermal sensations increased [1]. Choi et al. compared the EEG activity of participants who were under stress in a climate chamber where thermal, acoustic, and olfactory stimuli were combined to create an uncomfortable environment. They reported that the EEG power of high beta bands (21–30 Hz) were relatively high in participants who were placed in an uncomfortable environment where their stress was high [2]. The results of the present study, which showed a higher beta power in a subway platform that represented an uncomfortable environment, can be interpreted to be similar to the results of previous studies conducted in a laboratory. The result of the beta bands indicated that the participants experienced relatively more stress in an uncomfortable subway environment than a comfortable subway environment.

The results of the gamma bands were considered to be similar to the results of the beta bands. EEG activity of gamma bands are readily observable along with beta band activity in sensory processing and negative emotional processing [12,13]. A correlation between the two bands has been verified in many studies [14,15]. However, the EEG activity of the gamma band is related to a higher-level cognitive processing in the sensory system, including the auditory and visual systems. Its activity is thus more significant if more complex stimuli are provided. Pantev et al. verified that gamma band activity responds more significantly to auditory stimuli, and auditory linguistic stimuli induced an augmentation of gamma band activity [16,17]. In addition, gamma band activity was enhanced when high-level cognition processes such as learning, reading, and subtraction were performed [18]. In this study, there was a significant difference in the EEG power of gamma bands between the two environments, and higher EEG power of gamma bands was observed in the uncomfortable subway platform environment. The results of previous studies related with gamma band activity indicated that the uncomfortable subway platform environment in this study might have contained more complex stimuli, thereby evoking more cognitive processes. Choi et al. observed the brain activity of participants in a stressful combined environment of a climate chamber, and showed that there were no significant differences in the EEG powers of gamma bands [2]. This may have been due to the limitations of a laboratory-based study, which cannot fully simulate various stimuli in field factors that evoke attention that can be quantified.

Unlike the activities of the beta and gamma bands, which responds to stressful situations, the EEG power of alpha bands are known to increase in a stationary state such as when meditating or relaxing [19,20]. In a previous study conducted in the laboratory, the alpha bands of EEG signals have been reported to increase in comfortable environmental conditions. Yao et al. reported that the participants' alpha activity was highest in a cool thermal environment that was similar to a neutral environment, and decreased in uncomfortable thermal environments in a climate chamber [1]. Choi et al. reported that the participants' alpha activity ratio was relatively high in an environment where their stress was low; therefore, the alpha bands of EEG signals in the frontal lobe are useful for assessing a non-stressful environment [2]. The positive relationship between alpha power and comfort is due to a negative relationship between alpha bands activity and brain activity [21,22]. In other words, the argument that alpha bands activity increases in a comfortable environment is based on the premise that an indoor environment contains low-intensity stimuli that would rarely increase brain activity.

In a comparison of the results of previous studies related to gamma and alpha band activity, the comfort responses in the laboratory and those in the field environment should be interpreted differently because the context and reason for the occupant's response to comfort differ according to the environmental situation. The laboratory environment is a quiet and non-irritating environment, but the subway station is a space where there are noisy and diverse stimuli. A comfortable subway station is a less noisy and less unpleasant space than an unpleasant subway station, but it is not as quiet and irritating as a laboratory. From the beginning, we have different expectations for the two spaces. The evaluation of comfort is based on these different expectations.

The approach of brain activity can provide clues to track comfort-inducing mechanisms that cannot be analyzed in traditional survey methods. On the other hand, a data-driven approach using machine learning have been recently proposed as a new alternative approach [23–25]. Data-driven approaches require big data and real-time processing technology. Unlike traditional survey methods, brain activity measurements of biological signals in real-time for each frequency band per second is an appropriate approach to create big data containing the responses of participants. However, there is a lack of studies on observations of brain activity in a field environment. In the future, additional studies of brain activity measurements and analyses will allow brain activity measurements to be more useful with data-driven approaches.

## 5. Conclusion

Field experiments were conducted at comfortable and uncomfortable stations to comparatively measure EEG activity in 30 healthy students. The EEG signal patterns of the participants in the comfortable and uncomfortable subway stations showed that the beta and gamma band powers frequently increased in an uncomfortable environment as compared to the comfortable environment. The results indicated that the participants were less stressed relatively in an uncomfortable environment. These bands can be used as a relative indicator of discomfort.

Unlike previous studies, no specific pattern was observed in the other bands, in particular the alpha band. The result indicated that the participants were not significantly relaxed in platform 1 compared to platform 2. However, the participants evaluated the platform as comfortable. The result suggests the response to comfort was not an absolute response to the environment but a relative response based on environmental context and expectations.

There were differences between the results of previous studies conducted in the laboratory and the results of this study conducted in the field due to the differences between laboratory environments and the field environments. For example, the real world contains a great deal of movement and a range of environmental stimuli are present within it. In the laboratory, these stimuli cannot be simulated, and a participant's unexpected response to these stimuli cannot be observed. Unlike laboratory experiments, the participants' responses in the field should be analyzed considering the situation and context of the field. Brain activity measurements can be used to explain a participant's emotional and mental activity and to better understand the context of the field that the participant recognizes. Lastly, if more field studies are conducted with more samples in the future and data on brain activity patterns are accumulated, brain waves can be used as a useful indicator of comfort. Also, brain activity measurements of biological signals in real-time for each frequency band per second is an appropriate approach to create big data and real-time processing technology in near future.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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