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Gamma EEG Correlates of Haptic Preferences for a Dial Interface

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ABSTRACT Consumers often develop preferences toward consumer electronics based not only on the visual appearance of a product, but also on its haptic interface. If consumers express a strong haptic preference for a consumer electronic product, they are more likely to purchase it. Hence, it is important to understand how consumers' haptic preference for consumer electronics is formed. Conventional paper-based methods may not provide sufficient information for this purpose, because they provide post-event (i.e., after haptic experience) and environment-dependent (i.e., depending on the manner of asking questions, the person asking the questions, and so on.) data. Therefore, the present study investigated haptic preferences for consumer electronics using neural responses during haptic experiences, which provide the advantage of observing changes while the user is manipulating the product and obtaining environment-independent data. We measured neural responses using non-invasive electroencephalography (EEG). Eighteen volunteers participated in the study and manipulated a haptic dial knob that generates four different haptic profiles; during the manipulation, their EEG signals were recorded. After experiencing different haptic profiles, participants reported their level of preference for each profile. The analysis of EEG revealed that frontal gamma oscillations correlate with the level of haptic preferences, with oscillations becoming stronger with increasing haptic preference. The highest correlation between frontal gamma power and haptic preference was found in the early period of the dial task. Therefore, the frontal gamma oscillation of the EEG may represent a neural correlate of the haptic preference and provides a neural basis for understanding this preference in relation to consumer electronics.

INDEX TERMS Electroencephalography (EEG), haptic interfaces, brain computer interfaces.

I. INTRODUCTION

Preference is an important topic in consumer research [1], [2]. Consumer preference is influenced by product satisfaction and affects purchasing intentions [3]. Therefore, it has an essential role in developing brand preferences [4]. The sense of touch or haptic response has gained a lot of interest in consumer marketing research. Even though the sense of touch may not seem to be directly related to decision-making, it has been shown to influence the process and induce emotions [5]. Peck and Childers [6] reported that touch is able to influence impulse purchasing. Camargo and Henson performed an experiment to assess the effective impression of product packages with regard to touch, and Rahman investigated how visual and haptic sensations are able to influence a consumer's evaluation process [7], [8]. However, these studies were based on paper-based surveys and had several limitations. First, the human memory is often exaggerated or distorted [9], [10]. Therefore, the evaluation strays from the truth if there is a substantial time interval between the experience and the evaluation. With a conventional paper-based survey, participants inevitably answer questions after the experiment; thus, it is not possible to investigate the response of the participants during the experiment [11]. Moreover, participants sometimes have difficulty in expressing their experiences objectively in the case of ambiguous emotional status [12]. Thus, a neuroimaging modality in consumer studies has emerged as a potential solution to these problems. For example, Knutson *et al.* [13], [14] investigated brain activity during purchasing decisions by using functional magnetic resonance imaging (fMRI). Miltner *et al.* [15] used an electroencephalography (EEG) neuroimaging modality to find coherent EEG activity as a basis for associative learning. They reported that gamma-band EEG activity is related to the preference for certain colors. Müller*et al.* [16] showed significant differences for valence in the gamma-band, especially at 30–50 Hz, in an experiment using affective pictures. Gamma-band responses have been reported to differ in recognition of visual and auditory stimuli according to familiarity and congruity [17]. A previous study focused on EEG differences according to like/dislike selection of visual stimuli [18]. In studies investigating touch, researchers aimed to find EEG features corresponding to the users' pleasantness in response to passive touch stimuli [19], [20]. Moreover, previous studies have focused on touch on hairy skin [21]–[23]. However, for home appliances, active touch is mainly used, as customers use their fingers, which do not involve hair skin. Therefore, we investigated whether EEG correlated with preference according to haptic profiles by using an active motor task. We hypothesized that there would be a difference in the gamma-band as in conventional visual experiments [16].

II. MATERIALS AND METHODS

A. PARTICIPANTS

Eighteen volunteers (eight females, ten males; mean age = 21.8 ± 3.4 years; all right-handed) were recruited from several universities in Seoul, Korea, through online advertising. They participated in the experiment after submitting a written informed consent form, approved by the institutional review board of the Korea Institute of Science and Technology (IRB# 2014-002). We confirmed that all participants had no history of neurological, neuropsychiatric, or orthopedic diseases through a survey accompanying the informed consent form.

B. SETUP AND PROCEDURES

Fig. 1 shows the block diagram of the haptic dial interface system used to evaluate haptic preferences. The Biosemi system (Active-two, Biosemi^{TM}, Amsterdam, Netherlands) was used for recording 64-channel EEG data, dial trigger events, and dial task cue events. The dial task cue was displayed on the stimulation monitor, and the beep sound was played by the E-Prime software. The TMS 320 F 28335 digital signal processor controller was used to detect the moment of dial rotation following the dial task cue and sent a dial trigger event to the Biosemi system. It also detected the moment of completion of the dial task and then sent a task completion event to the E-Prime software. The dial knob on the front panel of a commercial washing machine was controlled by a direct current motor and various physical profiles were generated. Detailed information regarding the haptic dial system is described in our earlier publications [24], [25].

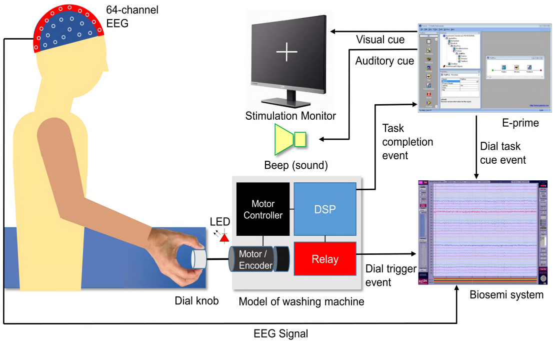

FIGURE 1. **Block diagram of the haptic dial interface and EEG recording system. The Biosemi system records 64-channel EEG signals, dial trigger events, and dial cue events. The DSP embedded system in the washing machine model controls the dial knob via a DC motor and measures the dial rotation angle using a motor encoder signal. The DSP also sends a task completion event to the control PC when the participants complete the dial task. DSP, digital signal processor; DC, direct current.**

Fig. 2(a) shows the four haptic profiles used in the experiment, as calculated by (1). Among the four profiles, profile A had the smallest value of A_v and the largest value of "s." Instead, profile D had the largest value of A_v and the smallest value of "s." The vertical axis in Fig. 2(a) indicates the torque of the dial knob and the horizontal axis indicates the notch interval rate (NIR). Each haptic profile represented a different NIR and torque. We defined NIR as the rate of the rotational angle between the invisible haptic notch interval and the visible angle interval between wash modes of the washing machine model shown in Fig. 2(b). Equation (2) shows the calculation of the NIR. We modulated the haptic profile of the dial knob using different parameters (torque and NIR). Profile A had smaller and profile D had bigger torque and NIR, respectively, than the original dial parameters of a washing machine. Meanwhile, profiles B and C had only slightly smaller and bigger torque and NIR, respectively, than the original dial knob parameter. Thus, profiles B and C represent common knob parameters of commercial washing machines.

$$T_\theta = A_v \sin\left(2\pi \cdot s \cdot NIR\right), \tag{1}$$

where A_v is the amplitude constant, s is the frequency scaling constant.

$$NIR = \theta_h / \theta_v, \tag{2}$$

where θ_h is the invisible haptic notch interval, and θ_v is the visible angle interval in the dial interface.

Fig. 2(c) shows a subject performing the task of rotating the dial knob, and Fig. 2(d) shows the subject self-reporting haptic preferences for a certain dial profile by pressing one

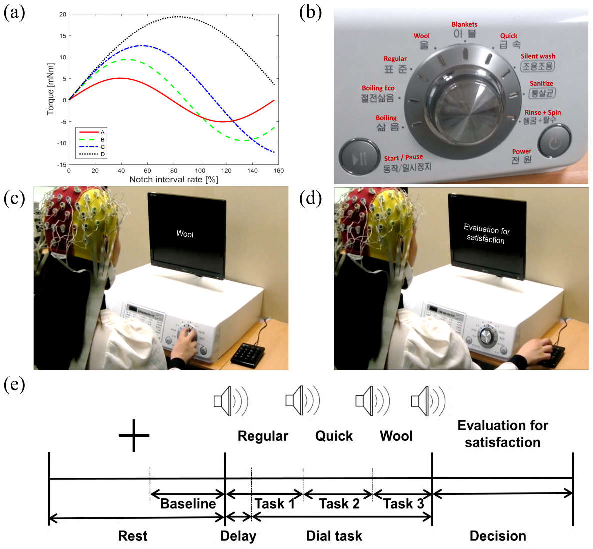

FIGURE 2. **(a) Four haptic profiles with different notch interval rates and relative torque. (b) Haptic dial knob for the panel of a washing machine. (c) Participant wearing a 64-channel EEG cap and performing the dial task of rotating a dial knob according to the directions on the monitor. (d) Participant evaluating haptic preferences during the decision period with a keypad. (e) Experimental trial protocol. The speaker images on the top row indicate a beep. The bottom row shows the monitor presentation. A cross indicates the fixation of the monitor during the rest period, and "Regular" "Quick" and "Wool" indicate the rotation path of the dial knob during the dial task period. "Evaluation for satisfaction" instructs the user to evaluate the haptic preferences.**

of the buttons on a keypad after the task. The haptic preference score (HPS) was on a scale of 1 (very dissatisfied) to 5 (very satisfied).

The experimental protocol consisted of six runs. Each run had 16 trials (four haptic profiles × four dial rotation scenarios) and the order was counterbalanced using the Latin Square. Each trial consisted of three periods: rest, dial task, and decision, as shown in Fig. 2(e). The rest period randomly lasted 2 or 3 s, as did the inter-trial interval. The dial rotation scenarios were designed not to affect haptic preference by the starting position, direction of rotation, and amount of rotation. All participants were asked to perform three consecutive dial rotation movements with different rotational directions and distances (Table I).

The rotational direction was represented as counterclockwise or clockwise. The distance was represented by the number of wash modes presented for a given rotational movement. The initial position of all dial tasks was "blanket". During the dial task, a target wash mode was displayed on the monitor, for example "wool," as shown in Fig. 2(c), with a short beep sound, and the physical position of the dial knob was recorded by a haptic dial system. "Delay" in Fig. 2(e) indicates the time from the dial task cue to the time the participant performed the dial knob rotation. The exact moment when the dial knob was rotated was recorded, by using a motor control embedded system. Finally, the participant evaluated the HPS during the decision period with a keypad, as shown in Fig. 2(d). EEG data were recorded throughout the experiment. The EEG signal acquired 1 s before the dial task was used as the reference EEG baseline signal.

C. EEG ACQUISITION AND DATA PROCESSING

EEG data were acquired with a sampling rate of 2048 Hz. The recorded data were preprocessed using EEGLAB [26]. In detail, EEG data were resampled at 1024 Hz, and a 1—80-Hz band pass filter and 60-Hz notch filter were applied. Since, artifactual components, such as electrooculography signals and muscle artifacts, may overlap with high-frequency neural activity [27], we removed artifact components using independent component analysis and via visual inspection [28]. Epoching based on haptic profiles and common average reference methods was employed [29]. After preprocessing, a spectrogram of the EEG signal at each channel was computed via the short-time Fourier transform with a 500-ms Hamming window, sliding by 50-ms. Spectral power was normalized by subtracting the baseline mean from every time point within an epoch and dividing this by the baseline standard deviation.

We investigated whether gamma-band oscillations were related to haptic preferences. In particular, the gamma band of 30-50 Hz has been shown to vary with visual valence [16]. Therefore, we selected the gamma-band frequency range of 30-50 Hz to investigate haptic preferences. We also investigated the possibility that other EEG oscillations might be correlated with haptic preferences. For example, human theta-band oscillations, as well as gamma-band oscillations, have been reported to correlate with facial preferences [30] and, thus, might also be modulated by haptic preference changes. Frontal alpha-band oscillations have also been implicated in affective valence [31], [32], and beta-band oscillations reflect emotional and cognitive processes [33]. Thus, they might reflect preference regarding haptic profiles. The frequency bands for theta (4–7 Hz), alpha (8–12 Hz), low beta (13–21 Hz), high beta (22–30 Hz), and gamma (31–50 Hz) bands were determined in a traditional manner [34]–[36]. To investigate the EEG correlates of haptic preferences, we extracted EEG power spectral densities (PSDs) at five EEG frequency bands according to (3) and (4).

$$PSD = \sum_{f=f_L}^{f=f_H} S_f \text{ and} \tag{3}$$

$$S_f = \frac{(\Delta t)^2}{T} \left| \sum_{n=1}^{N} x_n e^{-i\omega_n} \right|^2, \tag{4}$$

where f_H and f_L are the high and low cutoff frequencies of the particular frequency band, Δt is the sampling interval, T is the total measurement period and is $T = N\Delta t$, and x_n is the discrete time EEG signal.

D. ANALYSIS OF BEHAVIOR AND EEG CORRELATES

To analyze the behavior, HPS and PSD were normalized in order to have zero mean and unit variance. We investigated HPS differences between the four haptic profiles and the relationship between the HPS and the response time when a

TABLE 1. Rotation path of the dial knob during the dial task period.

Initial Position		Dial task		Direction			Distance (sum)			
	1st	2nd	3rd							
Blanket	Regular	Quick	Wool	CCW	CW	CCW	2	3	2	(7)
	Boiling	Wool	Silent	CCW	CW	CW	3	2	3	(8)
	Regular	Boiling Eco	Wool	CCW	CCW	CW	2	1	2	(5)
	Sanitize	Blanket	Rinse +Spin	CW	CCW	CW	3	3	4	(10)

The location of each washing mode presented in Fig. 2(b). The distance indicates the number of notches moved by the dial knob, and the distance (sum) indicates the total number of notches moved during the dial task period. Abbreviations: CCW, counterclockwise; CW, clockwise.

participant pressed a button on a response pad for evaluation, as shown in Fig. 2(d). We also explored the relationship between the HPS and PSDs across the five frequency bands and 64 channel locations during the dial task and decision periods, by using Pearson's linear correlation coefficient, r, as calculated using (5) and (6) [37].

$$r = \frac{\sum_{i=1}^{n}\left(HPS_i - H\bar{P}S\right)\left(PSD_i - P\bar{S}D\right)}{\sqrt{\sum_{i=1}^{n}\left(HPS_i - H\bar{P}S\right)^2 \sum_{i=1}^{n}\left(PSD_i - P\bar{S}D\right)^2}}, \quad (5)$$

where

$$\begin{aligned} &\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(HPS_i - H\bar{P}S\right)^2} \\ &\quad = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(PSD_i - P\bar{S}D\right)^2} = 1, \\ H\bar{P}S &= P\bar{S}D = 0. \\ r &= \frac{1}{n^4}\sum_{i=1}^{n} HPS_i \cdot PSD_i. \qquad (6) \end{aligned}$$

The dial task period was divided evenly into three sub-periods; early, middle, and late; in order to investigate the relationship in detail. Haptic preference was predicted using the most significant sub-period, among the three sub-periods, and the most significant frequency band power, among the five frequency bands.

The frontal EEG asymmetry is related to emotion [38]; thus, we calculated the correlation coefficients between the HPS and PSD asymmetry of the five frequency bands.

III. RESULTS

The four haptic profiles showed significant differences in the HPS. Fig. 3(a) shows that the HPSs for haptic profiles B and C were higher than those for haptic profiles A and D (repeated measures one-way ANOVA, $p < 0.01$). Fig. 3(b) shows significant differences in the response time, required for the evaluation of the HPSs. The response times were shorter when participants selected "very dissatisfied" (HPS $=$ 1) or "very satisfied" (HPS $=$ 5) compared to the other choices (repeated measures one-way ANOVA, $p < 0.01$). There was no significant difference in response times between the remaining three cases ("dissatisfied", "normal", and "satisfied").

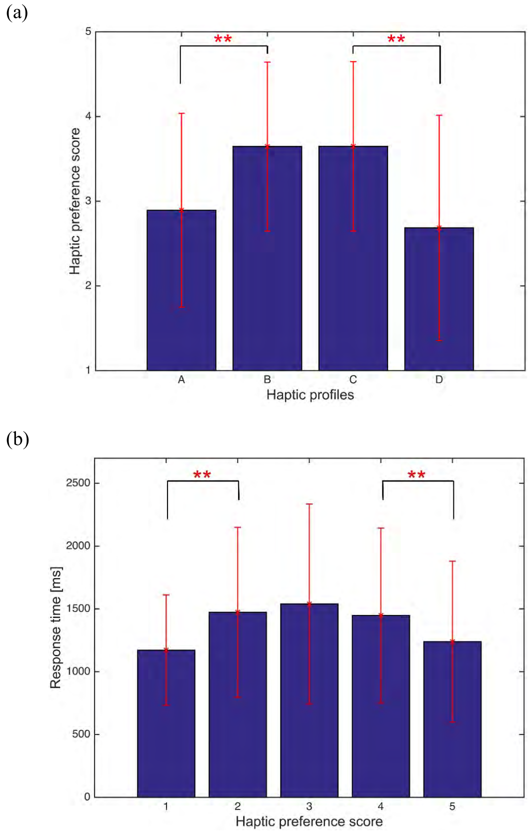

FIGURE 3. (a) Haptic preference scores (HPS) for each haptic profile. The bar height indicates the mean HPS and the error bar indicates the standard deviation. The preference for haptic profiles A and D is significantly higher than for profiles B and C. (b) Response time for scoring the haptic preferences. The bar height indicates the mean response time and the error bar indicates the standard deviation. The response time for HPSs 1 and 5 is significantly different from the one for HPSs 2, 3, and 4. **, $p < 0.01$, repeated measures one-way ANOVA; post-hoc, Tukey-Kramer.

The linear regression analysis of the 72 data points (four haptic profiles ×18 participants) for the normalized gamma PSDs and HPSs during the decision period at the

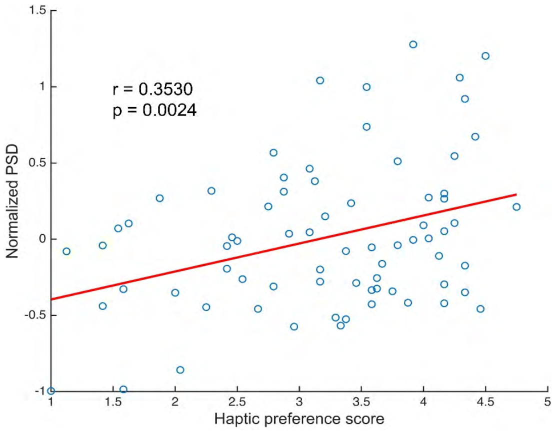

FIGURE 4. **Linear regression between the normalized power spectral density (PSD) and haptic preference score for the case of the gamma band and the AF8 EEG channel during the decision period (Pearson's linear correlation, $r = 0.3530$, $p = 0.0024$).**

AF8 channel location is shown in Fig. 4. The significant correlation indicates that the gamma oscillation in the right frontal area becomes stronger as the HPS increases (Pearson's linear correlation, $p < 0.01$).

Fig. 5(a) shows significantly related pairs of frequency bands and channel locations. Significant correlations were found between the normalized PSDs and HPSs during the dial task and decision periods. To verify that this significance was not caused by increase in Type I error due to multiple comparisons, we confirmed that all the results in Fig. 5 were statistically significant using the random permutation test [39], [40]. Neural correlates were detected in the high beta and gamma frequency bands during both the dial task and decision periods. Gamma band correlates were detected over a wider brain area. In particular, the right frontal (Fp2, AF4, and AF8 channels) gamma band EEG power was strongly correlated with the HPS during the decision period (Pearson's linear correlation, $p < 0.01$). Fig. 5(b) shows the EEG correlates of haptic preferences during each sub-period of the dial task (early, middle, and late) separately. Interestingly, the dominant EEG correlates of the haptic preferences were observed in the early period, but not the middle or late periods. Most of the channels with the strongest correlates were located around the frontal area. In addition, the distribution of gamma-correlated channels in the early period of the dial task was very similar to that in the decision period. In particular, the three channel locations at the right frontal area (Fp2, AF4, and AF8) showed strong gamma correlations to the haptic preferences in both the early period of the dial task and the decision period (Pearson linear correlation, $p < 0.01$). In the middle period of the dial task, only one high beta correlation was detected. In the late period the high beta and gamma correlates were weaker than those in the early period. No statistically meaningful relationship between the EEG asymmetry and HPS was found.

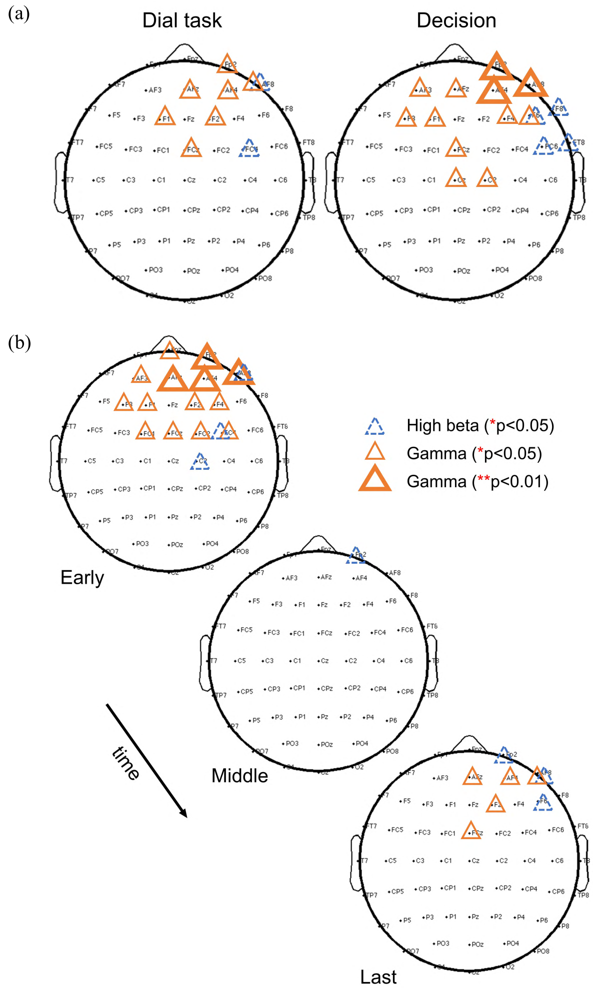

FIGURE 5. **(a) Significantly related combinations of frequency bands and channel locations during the dial task and decision periods. The blue-dashed triangles indicate a high beta band, the orange triangles indicate the gamma band, and the thick orange triangles indicate gamma bands with strong correlations. (b) Significantly related combinations of frequency bands and channel locations split equally into the early, middle, and late periods of the dial task (Pearson's linear correlation, $p < 0.05$; $p < 0.01$).**

Fig. 6 (a) shows the temporal changes in the normalized gamma-band power in the "very satisfied" and "very dissatisfied" conditions during the dial task in the right frontal area (AF8). The statistical differences between these two conditions (Wilcoxon rank sum test, $p < 0.05$) were also observed in the early period, in agreement with the gamma correlates of haptic preference that we found in this period (Fig. 5(b)). The changes in Pearson's linear correlation coefficient for the AF8, Fp2, AFz, and AF4 channels during the dial task are shown in Fig. 6 (b). The correlation coefficients in the early period were higher than those in the middle and late periods.

Significant correlations between normalized gamma PSDs and normalized HPSs were also found in the early period (Pearson's linear correlation, $p < 0.05$).

IV. DISCUSSION

Our study demonstrated that the gamma band oscillations of the frontal lobe are significantly correlated with haptic preferences. The cellular and synaptic mechanisms

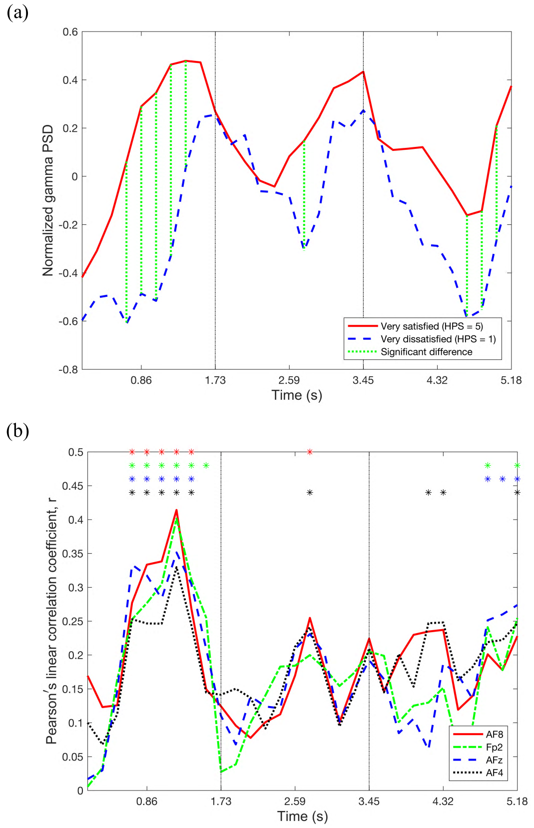

FIGURE 6. (a) Normalized gamma-band power spectral density (PSD) during the dial task in the right frontal area (AF8). The time range of 5.18 indicates the mean execution time of the dial task. The vertical black dashed lines indicate the early, middle, and late periods of the dial task period. The red-solid line and blue-dashed line indicate normalized gamma PSD in the "very satisfied" and "very dissatisfied" conditions. Vertical green-dotted lines indicate the significant difference in normalized gamma-band PSD between the "very satisfied" and "very dissatisfied" conditions (Wilcoxon rank sum test, $p < 0.05$). (b) Pearson's linear correlation coefficient, r, during the dial task. The four curved lines correspond to the EEG channel location; AF8, Fp2, AFz, and AF4 in the frontal brain area. Four asterisks indicate significantly meaningful correlations between normalized gamma PSDs and normalized haptic preference score in the four channel locations, respectively (Pearson's linear correlation, $p < 0.05$).

of gamma band oscillations have been previously elucidated [41]. Gamma band oscillations are related to cognitive processes, including attention, arousal, object recognition, and language perception [42]. Başar reported that sensory-cognitive dynamics and emotions are also correlated with gamma band oscillations [43]. Previous studies have reported that object recognition and perception processing are associated with gamma band oscillations [44]–[47]. These findings are consistent with our results.

During the dial task period, we showed that strong EEG correlates of gamma band oscillations with haptic preferences are more dominant in the early period of the dial task than in the middle and late periods. The dial task was composed of three target positions (sub-tasks) and this period was split by three equal periods. Each sub-period corresponded to the averaged elapsed time to rotate the dial knob from the current position to the next target position. The participants could feel and evaluate the haptic profile for each sub-period. There were many significant gamma power differences between "very satisfied" and "very dissatisfied" conditions, and significant frontal gamma correlations of haptic preferences in the early period. This may be because the initial impression from the sense of touch was very important and may have strongly affected the haptic preference. In agreement, it was shown that people may decide on a website's design from their first visual impression [48]. During the late period of the dial task, we observed right-frontal gamma band correlations, which may be due to the participants' expectation or preparation to evaluate the preference level.

In general, time-locked experimental protocols and analyses are used for this type of EEG studies. However, we chose an active task because we wanted to know how the EEG differs during preference selection according to the actual machine manipulation. Our experiment cannot create a time-locked task period like a passive stimulus experiment would because the participants performed the dial task at their own pace.

We also showed that most of all correlated channels were located in the frontal lobe area. Specifically, channels that strongly correlated with gamma bands were located in the right frontal area during both the decision and early periods of the dial task. The prefrontal cortex is known to be related to decision-making, emotional responses, and attention functions [49], [50]. An fMRI study reported that the prefrontal cortex plays a critical role in tactile decision processing [51]. Other studies have also reported that the right side of the prefrontal lobe is associated with feeling-of-knowing judgments, in addition to positive and negative valence emotions [16], [52]. Therefore, it is reasonable that the EEG data from the right-frontal area were associated with haptic preferences. However, this correlation does not prove a causal relationship.

Lin *et al.* [53] investigated EEG activity depending on haptic feedback in a visuomotor tracking task. They showed that the left frontal component cluster exhibited strong gamma-band suppression in the haptic feedback condition. This work suggest that the source of right frontal gamma oscillation may be located in the right frontal areas.

We also conducted within-individual analysis; however, the results of the correlations between gamma EEG and haptic preference for each participant were inconsistent. This may be because of the large individual differences in the EEG characteristics [54].

From the behavior analysis, the four haptic profiles showed significant differences in the HPS. This result indicates that the four haptic profiles provide different HPSs to the participants. Moreover, the response times when the participant selected either "very satisfied" or "very dissatisfied" as the preference level were significantly shorter than the other choices. In contrast, there was no significant difference in response times between the cases of "satisfied", "normal", and "dissatisfied". These results indicate that the overt emotional status can be measured through behavior analyses such as response time measurements or paper-based surveys; however, ambiguous emotional statuses are difficult to assess. Consequently, the use of gamma EEG is advantageous for the measurement of haptic preferences. This also allows us to overcome the conventional paper-based survey's issue of bias due to posture, questionnaire atmosphere, questioner's manners, or social relations between the person who conducts the survey and the subjects participating in it.

V. CONCLUSION

Most previous neuroimaging studies have focused on visual appearance to evaluate consumer preferences for different products; however, little is known about haptic preferences because of the difficulty of setting up experimentally controlled conditions. Dial interfaces are widely used for consumer products, including washing machines, automobiles, cameras, and radios. Thus, we used a haptic dial system to generate various haptic profiles. EEG correlates of haptic preference were investigated by using a haptic dial knob interface with four distinct profiles and various combinations of NIRs and torques. Participants were asked to evaluate their haptic preference by rotating the dial knob of the washing machine model. The findings suggest that the frontal gamma band oscillations are significantly correlated with HPS during both the early and the decision periods of the dial task. In particular, strong right frontal gamma correlates occurred during these time periods. In conclusion, we developed a novel EEG-based haptic preference measurement technique, which provides the advantage of observing changes in tasks without the influence of the survey environment.

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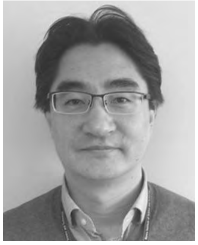

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