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Frontal EEG Asymmetry of Emotion for the Same Auditory Stimulus

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ABSTRACT Emotions play an important role in human interaction and decision-making processes. Frontal asymmetry in brain activity is a promising neurophysiological indicator of emotion. Emotions are psychologically explained by the valence-arousal model, but as yet, frontal asymmetry has not been fully explained by this model. In this study, we explored frontal asymmetry of emotions based on the valence-arousal model using the same auditory stimulus. Changes in emotional states using self-report questionnaires were investigated before and after the auditory stimulus. Spectral power and weighted phase lag index were calculated in the delta, theta, alpha, beta, and gamma bands. Phase-amplitude coupling was also measured to explore communication among different frequency bands associated with emotions. After the auditory stimulus, alpha power decreased in both left and right frontal regions and the delta-weighted phase lag index in the left-right regions was increased. However, no frontal asymmetry was identified after the auditory stimulus. Additionally, we explored the brain changes according to the valence-arousal model based on emotional states. After the auditory stimulus, frontal asymmetry of alpha power was clearly observed only for negative valence. This finding was possible because subjective emotions were considered despite listening to the same stimulus. Finally, phase-amplitude coupling identified left-hemisphere dominance after the auditory stimulus, regardless of subjective emotions. These results may help us understand frontal asymmetry associated with emotional mechanisms. In addition, these findings can be used directly in the brain-computer interface to improve emotion recognition performance for real-world practical applications.

INDEX TERMS Electroencephalogram (EEG), emotion, frontal asymmetry, power spectral density (PSD), weighted phase lag index (WPLI), phase-amplitude coupling (PAC).

I. INTRODUCTION

Emotion refers to a human state that occurs in response to the perception of an object or situation, and which plays a major role in human interactions, decision-making processes, and everyday life [1]. The modulation of emotion is associated with the structure and function of the limbic and paralimbic systems [2]. Human emotion can typically be conceptualized as a two-dimensional model involving valence and arousal as the vertical and horizontal axes [3]. Specifically, the valence dimension represents positive or negative affectivity (pleasant or unpleasant), whereas the arousal dimension represents high or low affectivity (from calming to exciting) [4]. In other words, positive valence means positive emotions and negative valence means negative emotions. On the other hand, arousal is a measure of excitation [5]. Therefore, many studies have been investigated using this two-dimensional valence-arousal emotion model. For example, fear is associated with a state of high arousal and negative valence, whereas excitement is characterized by high arousal and positive valence. However, it is difficult to distinguish similar emotions in the valence and arousal dimensions [6]. An alternative is to use physiological characteristics, such as brain activity, in conjunction with the valence-arousal model to better investigate emotional responses.

According to emotional cognitive theory, the brain is the primary source of emotional responses because it processes thoughts about behavior and emotions [7]. Many studies

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have distinguished emotional states using electroencephalography (EEG) signals [8]. Because EEG is inexpensive and has high temporal resolution, it is practical [9]. Visual, audio, and speech stimuli induce a variety of psychological changes, such as changes in perception, attention, behavior, and cognitive processing [10]. Auditory stimuli can directly modulate the brain activity of the limbic and paralimbic regions associated with emotions and are therefore suitable for inducing positive or negative and high or low emotions [11].

Most EEG studies on the emotional response have focused on the spectral power dependent on an auditory stimulus. Delta activity is enhanced overall in brain regions while listening to music [12]. In addition, theta power in frontal regions is modulated as a function of affective processing in response to dissonant music [5]. In some cases, theta power is increased while listening to music [13]. Alpha power in frontal regions plays a major role in distinguishing positively and negatively valenced emotions [14]. Some studies have reported decreased alpha power in frontal regions [15], [16], while other studies have shown increased alpha power in frontal regions after listening to music [13], [17]. Finally, beta and gamma activities are related to arousal modulation and arousal effects, respectively [18]. To date, several studies have reported changes in spectral power following an auditory stimulus, but brain changes according to auditory stimuli associated with emotions remain unclear [19]. How each frequency band interacts with emotion also remains unknown.

In recent years, many studies have tried to use brain connectivity to understand emotion recognition [20]–[22]. These characteristics are important in that they indicate not only brain activity in specific regions, but brain interactions between regions. In other words, brain connectivity can shed light on how different brain regions are coactivated and communicated [23], [24]. In particular, the brain network of the frontal region plays a role in controlling emotions [25]. Some studies have reported increased delta connectivity after listening to music [12]. Delta synchronization increases with both pleasant and unpleasant stimuli [26]. In addition, brain connectivity in the delta, theta, and alpha bands is enhanced for affective gestures [18]. Phase synchrony in the beta and gamma bands is increased in post-stimulus [4]. The functional connectivity in the beta and gamma bands while listening to music is associated with auditory and motor interactions [27]. However, brain connectivity associated with emotion processing is less well understood.

Frontal EEG asymmetry refers to the difference in brain activity between the left and right frontal regions [12], [28]. This phenomenon is directly related to emotion and is used to recognize emotion [29]. Positive emotions are specifically associated with left hemisphere activity, whereas negative emotions are associated with more right hemispheric activity [30], [31]. This frontal asymmetry between the left and right frontal regions is also observed in relation to brain connectivity [25]. In some cases, however, there is no change in frontal asymmetry after the auditory stimulus [32]. In other words, research about the brain mechanisms associated with frontal asymmetry is necessary.

In this study, we investigated changes in spectral power and brain connectivity during auditory stimuli and frontal EEG asymmetry associated with emotions in post-stimulus. Natural sounds were used as auditory stimuli. Usually, these sounds are expected to elicit positive emotions [33], but we expected that they would elicit different emotions. Delta and alpha bands play an important role in the emotion regulation process [15], [34]. In this regard, we hypothesized that the brain signals may differ with subjective emotions, especially in delta and alpha bands, even if participants listened to the same auditory stimulus. Finally, phase-amplitude coupling (PAC) was analyzed to investigate the relationship between delta and alpha bands to identify associations with emotion [35], [36].

The contributions of this study can be summarized as follows: (i) an explanation of frontal asymmetry according to the valence-arousal emotion model using the same auditory stimulus; (ii) an analysis of brain connectivity between brain regions and the relationship between frequency pairs for PAC, as well as simple changes in a given brain region; and (iii) comparison of frontal asymmetry in spectral, spatial, and temporal changes after the auditory stimulus.

The remainder of this paper is organized as follows. Section II presents relevant research on emotions following an auditory stimulus and frontal EEG asymmetry of emotion. Section III describes the research methods. Sections IV and V present the results and discussion, respectively. Finally, Section VI draws conclusions.

II. RELATED RESEARCH

In this section, we briefly review the existing studies of emotion in response to auditory stimuli and frontal EEG asymmetry regarding emotional changes.

A. EMOTION IN RESPONSE TO AUDITORY STIMULI

Our emotions change in response to various auditory stimuli. Considerable research has reported on EEG characteristics of emotion processing. For example, spectral power is a useful feature in emotion recognition studies using EEG [8]. Du and Lee [37] investigated emotional responses induced by three auditory stimuli (unpleasant, neutral, and pleasant). Arjmand *et al.* [38] showed physiological and subjective measures of experienced emotion when listening to four auditory stimuli (unpleasant, neutral, pleasant, no music). Significant changes in frontal asymmetry are typically observed in response to pleasurable music. In Höller *et al.* [39], alpha and beta oscillations were found to be responsive when listening to one's favorite music. The main effect is a desynchronization in the low alpha band and synchronization in the high alpha band according to personal preference.

More recently, some researchers have noted brain connectivity when processing emotion in response to auditory stimuli [40]. Alipour *et al.* [27] found that alpha connectivity of the fronto-central connections was primarily

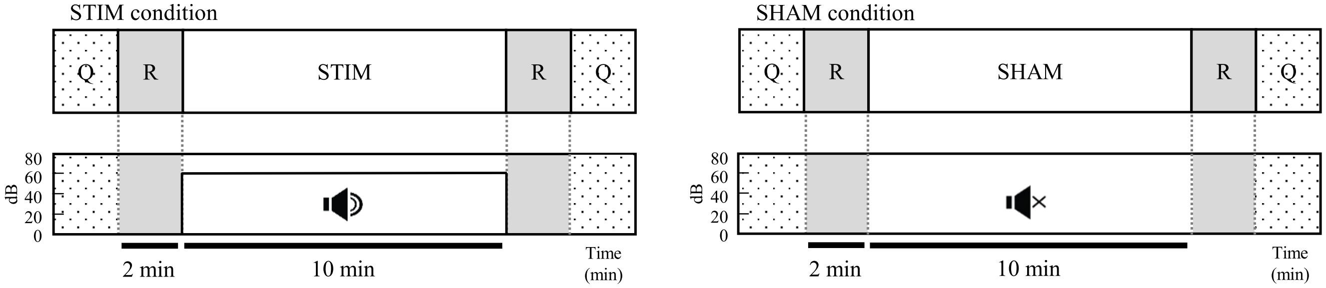

FIGURE 1. Experimental paradigm. The experiment consisted of stimulation (STIM) and sham (SHAM) conditions. A natural sound at 60 dB was provided during STIM, whereas no sound was provided during SHAM. Both conditions were presented in random order. Q = questionnaire, R = resting-state.

associated with emotional music, especially in valence. In Zhang *et al.* [41], significant differences in effective connectivity were found between positive and negative emotions. Specifically, frontal regions and connectivity with other regions play a critical role in emotion processing. The relationship between frequencies, using cross-frequency coupling, is an emerging technique to investigate the association of many frequencies with emotions. Lakatos *et al.* [42] reported that the amplitude of gamma oscillations was modulated by the phase of theta oscillations during auditory stimuli. Cross-frequency coupling between theta phase and gamma amplitude is considered to be important for auditory processing.

Currently, many studies have reported changes in EEG features according to auditory stimuli. However, no studies have investigated changes in spectral power, brain connectivity, and cross-frequency coupling simultaneously when listening to the same auditory stimuli. We investigated these EEG features using natural sounds to better investigate the emotional response elicited by auditory stimuli.

B. FRONTAL EEG ASYMMETRY OF EMOTION

Over recent decades, many studies have reported on frontal EEG asymmetry in response to emotion in terms of spectral power. Wheeler *et al.* [43] were the first to propose the relation between frontal asymmetry and emotion. Specifically, positive and negative emotions are mostly processed in the left and right frontal brain regions, respectively, when watching affective film clips. Schmidt and Trainor [14] suggested that the reason for the lateralization of alpha power is because of the opposite (positive vs. negative) valence induced by musical excerpts. Zhao *et al.* [44] elicited the difference in two positive (amusement and tenderness) and two negative (anger and fear) emotions using theta and alpha frontal asymmetry when exposed to emotional film pieces. It is important that these findings explain brain differences between two separate emotions that are similar in the valence-arousal model. Another study showed that resting alpha frontal asymmetry reflects personal preferences [45]. They evaluated neutral, positive, or negative emotions in response to music. Specifically, participants with more relative left frontal activity rated musical stimuli more positively than did those with less relative right frontal activity.

In recent years, some studies have investigated frontal asymmetry, noting the relationships between regions using brain connectivity and associations between frequencies using cross-frequency coupling to reflect neural communications [25], [46]. Geethanjali *et al.* [47] showed asymmetrical alpha connectivity in frontal regions according to personal preferences. If the participant listens to preferred Indian music, alpha connectivity in left frontal regions was lower as compared to right frontal regions. Daly *et al.* [40] observed many neural correlates of emotions using musical stimuli. Specifically, long-range cortical connectivity in emotional processing was found. Adamos *et al.* [48] found that cross-frequency coupling quantified music-induced emotions using dynamic connections between frequencies. They focused on functional coupling between high beta and low gamma frequencies in left prefrontal cortex and argued that this measure could be a biomarker of music preferences.

Thus far, many studies have reported on emotions and personal preferences as reflected in frontal EEG asymmetry, but they have typically presented different stimuli. Therefore, it is unclear whether the brain changes caused by different stimuli are obviously induced by emotion or personal preferences. In this study, we investigated differences in frontal asymmetry in response to emotions or personal preferences based on the same stimulus.

III. METHODS

A. PARTICIPANTS

Data from 16 participants (four females; age 24.6 ± 1.6 years) were used in this study. The participants had no history of any neurological, psychiatric, or hearing problems. This study was approved by the Institutional Review Board at Korea University (KUIRB-2019-0134-01), and all participants gave written informed consent before the experiments. The experiments were performed in accordance with the Declaration of Helsinki.

B. EXPERIMENTAL PROCEDURE

Each participant was asked to sit on a chair in the laboratory. They completed a questionnaire about their emotional state before and after the auditory stimuli. EEG signals were recorded for 14 min; 2 min before and after the auditory stimulus, and 10 min during the auditory stimulus (Fig. 1). This was because the effects of auditory stimuli are transmitted to all brain regions when exposed for approximately 10 min [49], [50]. In addition, the experiments were carried out with participants' eyes closed to reduce ocular artifacts and increase concentration [51].

The experimental procedure was carried out according to a randomized crossover design. Specifically, the auditory component consisted of a stimulation condition (STIM) and a sham condition (SHAM), which were randomly assigned to participants. The STIM was randomly selected from five natural sounds (rain, sea waves, waterfall, forest, and river) on YouTube (http://www.youtube.com) [50], as spatial patterns whilst listening to various natural sounds are similar [52]. This sound was delivered through in-ear earphones at 60 dB [53]. In the SHAM, no sound was heard (0 dB) whilst wearing earphones.

We also examined changes in psychological stability before and after the auditory stimulus. The Brunel mood scale (BRUMS) is a self-reported emotional state consisting of 32 items [54]. Participants indicate the degree to which they relate to eight emotions: "anger," "tension," "depression," "vigour," "fatigue," "confusion," "happy," and "calmness" [55]. For each emotion, a response was given based on the 5-point Likert-type scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, and 4 = extremely).

C. VALIDATION OF SELF-REPORTED EMOTIONAL STATES

We measured the BRUMS-32 questionnaire before and after the auditory stimulus to investigate the emotional changes. Validation was performed using exploratory factor analysis, as self-report can be biased [56], [57]. Specifically, two conformance verifications were used to verify the self-report BRUMS-32 questionnaire. First, the sampling adequacy was evaluated by examining the Kaiser-Meyer-Olkin (KMO) values, which can range from 0 to 1. This value indicates how well the correlation between the variables is explained by other variables [58]. If the KMO value is less than 0.05, the sampling is not adequate [59]. In contrast, a KMO value above 0.60 to 0.70 indicates that the sampling is adequate. Second, Bartlett's test of sphericity was conducted to assess the strength of the relationship among emotions [60]. A significant value less than 0.05 means that raw data approximate a multivariate normal distribution [61].

Exploratory factor analysis was used to convert the self-reported eight emotions to correlated unobserved factors. This method is a statistical analysis that identifies new common variables that can be described in a dataset with multiple interrelated variables [59]. Specifically, the maximum likelihood extraction with direct oblimin rotation was used. The eigenvalues (≥ 1) were used to determine the required number of meaningful factors. We set 0.4 as the threshold for a rotated factor to find items with common characteristics [62]. We expected the BRUMS-32 questionnaire items to be converted into valence-arousal coordinate space with two factors [3]. Participants were grouped according to their emotional state after listening to the same auditory stimuli as follows: (i) valence dimension: positive or negative groups and (ii) arousal dimension: high or low groups.

D. EEG DATA RECORDING AND PREPROCESSING

The EEG data were recorded using an amplifier (BrainAmp; Brain Project GmBH, Germany). The 19 Ag/AgCl electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, and O2) were used according to the 10-20 international system. The sampling rate was 500 Hz. FCz was used as the reference electrode and AFz was used as the ground electrode. Electrode impedance was maintained below 10 kΩ.

The EEG signals were analyzed using MATLAB R2018b with EEGLAB toolbox [63]. Data were down-sampled to 250 Hz and band-pass filtered from 0.5 to 50 Hz [64]. The 2-min resting state before and after the auditory stimulus was segmented into 10-sec intervals [65], and the 10-min auditory stimulus period was also segmented into 10-sec intervals. To remove noise, including ocular and muscle artifacts, the contaminated channels were interpolated using the spherical method and the segments were excluded when the amplitude value exceeded a threshold of ± 100 µV [66].

E. EEG DATA ANALYSIS

We divided the brain changes into (i) during auditory stimuli and (ii) after auditory stimuli. During auditory stimuli, all brain regions (19 channels) were used. In addition, only six channels (left frontal region: Fp1, F3, and F7; right frontal region: Fp2, F4, and F8) were calculated to investigate frontal asymmetry after auditory stimuli. The changes in auditory stimuli were explored in five frequencies as follows: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz) bands [67].

1) SPECTRAL POWER ANALYSIS

We extracted five EEG frequencies using the fast Fourier transform (FFT), which converts from the time to the frequency domains [68]. The power spectral density (PSD) of a specific channel c with the down-sampling frequency of f_s was calculated as follows [69]:

$$P^c(f) = \frac{1}{f_s N} \left| \sum_{n=0}^{N-1} x_n^c e^{-j2\pi fn} \right|^2 \tag{1}$$

where x_n^c indicates the time domain data of channel c with N samples ($-f_s/2 < f < f_s/2$). P_w^c is defined to compute the PSD of channel c signal in frequency band $w = [w1, w2]$ as follows:

$$P_w^c = 10 * log_{10} \frac{\sum_{f=w1}^{f=w2} P^c(f)}{\sum_{f=0}^{f=\frac{f_2}{2}} P^c(f)} \tag{2}$$

where $w1$ and $w2$ represent the lower and upper frequencies, respectively. The unit conversion from microvolts to decibels

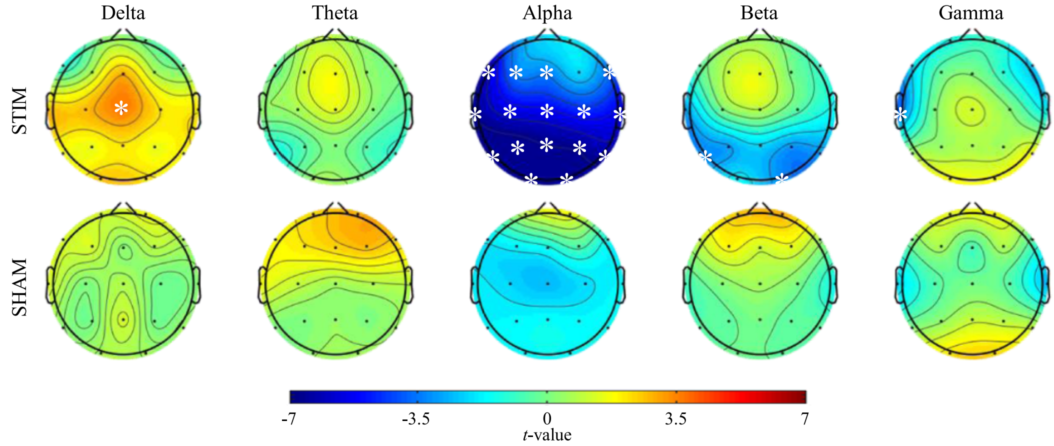

FIGURE 2. **Differences in spectral power between the baseline and the stimulus period for STIM and SHAM. The statistical results represent t-values in each frequency band for differences between the baseline and the stimulus period using a paired-samples t-test. Blue regions reflect decreased activity during the stimulus, whereas orange channels reflect increased activity during stimulus compared to baseline. The baseline (pre-stimulus) was 2 min before the auditory stimulus. The white asterisk indicates a significant electrode in spectral power between the pre-stimulus and stimulus periods ($p < 0.05$ with Bonferroni's correction). PSD = power spectral density, STIM = stimulation condition, SHAM = sham condition.**

is denoted as $10 * log_{10}(\bullet)$. Spectral power was calculated in each trial and then averaged over trials for each participant. For frontal asymmetry after the auditory stimuli, the averaged spectral power was also averaged in left frontal (Fp1, F3, and F7) and right frontal regions (Fp2, F4, and F8).

2) FUNCTIONAL CONNECTIVITY ANALYSIS

To investigate the functional connectivity between two channels, we used the weighted phase lag index (wPLI) [70]. This measure computes the difference in phase synchronization between pairs of channels. Specifically, wPLI was calculated to minimize the impact of volume conduction and the number of artifacts [27], [50]:

$$wPLI = \frac{|E\{\mathcal{J}\{X\}\}|}{E\{|\mathcal{J}\{X\}|\}} = \frac{|E\{|\mathcal{J}\{X\}|sgn(\mathcal{J}\{X\})\}|}{E\{|\mathcal{J}\{X\}|\}} \tag{3}$$

where $\mathcal{J}\{X\}$ indicates the imaginary component of the cross-spectrum $X = Z_i Z_j^*$ between two channels i and j, Z_i is the complex-valued Fourier transform of the signal of channel i, Z_j^* is the complex conjugate of Z_j, and $E\{\bullet\}$ is the expected-value operator. The 19×19 wPLI matrices over each frequency band were computed in averaged trials. For frontal asymmetry, the wPLI was averaged (i) within left frontal (Fp1-F3, Fp1-F7, and F3-F7) or right frontal regions (Fp2-F4, Fp2-F8, and F4-F8) and (ii) between left and right (inter) frontal regions (Fp1-Fp2, Fp1-F4, Fp1-F8, Fp2-F3, Fp2-F7, F3-F4, F3-F8, F7-F4, and F7-F8), respectively.

3) PHASE-AMPLITUDE COUPLING ANALYSIS

PAC is a suitable method for exploring how different frequencies communicate by identifying the relationship between the phase of low-frequency signals and the amplitude of high-frequency signals [35]. We investigated the relationship between phase of delta band and the amplitude of alpha bands in that we focused on delta and alpha bands associated with emotions. Modulation index (MI) is a measure based on the same parameters of amplitude magnitude and phase angle for PAC [35]. This was calculated as the Kullback-Leibler (KL) divergence between the uniform distribution and the observed probability density, which describes the normalized mean amplitude at a given binned phase. Based on the alpha-amplitude series, surrogate data ($r = 2{,}000$) was generated by circularly permuting the delta-phase time-series. MI was calculated if it exceeded 95% MI of the surrogate values ($p < 0.05$) [71], [72]:

$$p(j) = \frac{A_{f_A \O f_P}(j)}{\sum_{k=1}^{N} A_{f_A \O f_P}(k)} \tag{4}$$

where $A_{f_A \O f_P}(j)$ is the mean f_A alpha-amplitude signal at phase bin j of the delta-phase signal $\O f_P$. We divided the phase into 36 bins of 10-degree intervals:

$$D_{KL}(P, Q) = \sum_{j=1}^{N} P(j) \log \frac{P(j)}{Q(j)} \tag{5}$$

where D_{KL} is the KL divergence, P is the observed phase-amplitude probability density function, Q is the uniform distribution, and N is the number of phase bins. MI is the KL divergence divided by $\log N$ as follows:

$$MI = \frac{D_{KL}(P, Q)}{\log N} \tag{6}$$

A larger MI value indicates a more nonuniform distribution of amplitude conditioned on phase, which can be regarded as a stronger PAC intensity. Finally, MI between delta phase and alpha amplitude was computed in each channel and then averaged in left and right frontal regions to investigate frontal asymmetry.

We additionally measured the laterality index (LI) to investigate the hemispheric dominance associated with frontal asymmetry of emotions [73]:

$$LI = (L - R)/(L + R) \tag{7}$$

where L and R represent left and right frontal regions. LI values of MI were calculated between -1 and 1. A positive value indicates left-hemisphere dominance whereas a negative value indicates right-hemisphere dominance [74]. Here, left and right frontal hemispheres refer to the averaged MI in left and right frontal regions, respectively.

F. STATISTICAL ANALYSIS

To investigate changes during the auditory stimulus compared to baseline (pre-stimulus), a two-way analysis of variance (ANOVA) was applied to the spectral power and wPLI. One factor was channel (spatial information) and the other factor was time (baseline vs. stimulus period). For post-hoc analysis, a paired t-test was used with Bonferroni's correction. We also performed a two-way ANOVA (condition × time) for spectral power, wPLI, and MI to explore the difference of frontal asymmetry in both conditions (STIM and SHAM) and time (before vs. after the auditory stimulus) associated with emotions. Then, a paired t-test with Bonferroni's correction was applied for post-hoc analysis. For hemisphere dominance, a one-sample t-test was performed to determine if the LI of the MI was statistically positive or negative.

For psychological changes, a paired t-test with Bonferroni's correction was used to compare the difference in BRUMS-32 scores before and after the auditory stimulus, and between STIM and SHAM.

In addition, Friedman's test (non-parametric two-way ANOVA) was applied for statistical comparison of spectral power, wPLI, and MI in the valence and arousal groups after exploratory factor analysis. For post-hoc analysis, the paired non-parametric permutation test was performed with Bonferroni's correction ($r = 1{,}000$). In addition, the one-sample non-parametric permutation test was used for the LI of the MI related to hemisphere dominance ($r = 1{,}000$). All significance levels in this study were $\alpha = 0.05$.

IV. RESULTS

A. CHANGES IN EEG FOR THE AUDITORY STIMULUS

1) CHANGES IN EEG DURING THE AUDITORY STIMULUS

We investigated significant changes during the 10-min auditory stimulus period compared to baseline (pre-stimulus). Specifically, there were spatial differences in spectral power between the 19 channels in both STIM and SHAM. We focused on temporal differences during the auditory stimulus (Fig. 2). In STIM, there were mainly statistical changes in the alpha band compared to pre-stimulus. In particular, alpha activity was significantly reduced over all regions except for prefrontal regions. However, no temporal differences between pre-stimulus and stimulus periods were observed in SHAM for any of the five frequency bands.

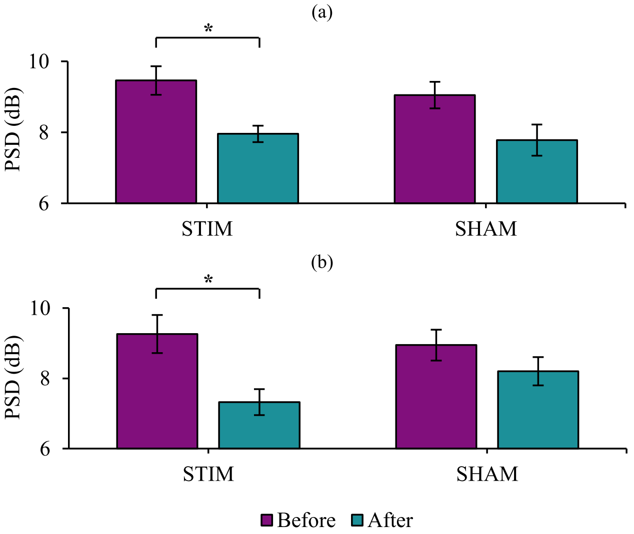

FIGURE 3. Changes in alpha power post-stimulus in frontal regions. In the (a) left and (b) right frontal regions, alpha power was observed pre- and post-stimulus for both STIM and SHAM. Error bars show standard errors. PSD = power spectral density, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

Similarly, we explored the changes in wPLI during the auditory stimulus at the five frequencies. There were spatial differences in wPLI between all connections in the delta, theta, alpha, beta, and gamma bands. However, no clear temporal change at any frequency band was observed between baseline (pre-stimulus) and the auditory stimulus was observed in either STIM or SHAM.

2) SPECTRAL POWER IN FRONTAL ASYMMETRY AFTER THE AUDITORY STIMULUS

To examine frontal EEG asymmetry according to the auditory stimulus, we calculated the spectral power in five frequency bands before and after the stimulus. Table 1 shows the significant differences between before and after the auditory stimulus in both the left and right frontal regions. We focused on temporal changes in PSD after the auditory stimulus. Specifically, in STIM, alpha power post-stimulus was significantly lower than it was pre-stimulus in both frontal regions (left: $t = -4.091, p < 0.001$; right: $t = -4.131, p < 0.001$; Fig. 3). However, there was no frontal asymmetry in alpha power changes post-stimulus. Similarly, no significant changes in alpha power were observed in SHAM post-stimulus. In addition, there was no difference before and after stimulus in other frequency bands.

3) FUNCTIONAL CONNECTIVITY IN FRONTAL ASYMMETRY AFTER THE AUDITORY STIMULUS

Changes in frontal asymmetry between brain regions were explored after the auditory stimulus. Significant differences in wPLI were observed over the left, right, and inter (left-right) frontal regions (Table 2). We found a difference in the beta wPLI over left frontal region and gamma wPLI over left-right frontal regions before and after the stimulus according to the ANOVA results, but there was no difference according to

TABLE 1. Statistical results in pre- and post-stimulus for PSD in the frontal region. The time factor indicates pre- and post-stimulus, whereas the condition factor indicates the STIM and SHAM. The time × condition represents the interaction between time and condition factors. The *p*-values less than 0.05 are shown in bold. PSD = power spectral density, STIM = stimulation condition, SHAM = sham condition.

Region	Factor	Delta		Theta		Alpha		Beta		Gamma	
		F	*p*-value	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value
Left frontal region	Time	0.22	0.641	0.02	0.887	13.97	**<0.001**	0.73	0.396	0.68	0.411
	Condition	1.11	0.296	0.05	0.820	0.62	0.433	1.81	0.184	1.23	0.272
	Time × Condition	0.93	0.339	0.35	0.555	0.10	0.752	0.30	0.588	0.48	0.492
Right frontal region	Time	0.01	0.993	0.04	0.833	9.14	**0.004**	0.03	0.874	1.55	0.218
	Condition	6.68	**0.012**	1.47	0.230	0.40	0.527	0.18	0.674	0.24	0.626
	Time × Condition	2.03	0.160	1.76	0.190	1.82	0.183	2.97	0.090	3.78	0.057

TABLE 2. Statistical results in pre- and post-stimulus for wPLI in frontal regions. The time factor indicates pre- and post-stimulus, whereas the condition factor indicates STIM and SHAM. The time × condition represents the interaction between time and condition factors. The *p*-values less than 0.05 are shown in bold. wPLI = weighted phase lag index, STIM = stimulation condition, SHAM = sham condition.

Region	Factor	Delta		Theta		Alpha		Beta		Gamma	
		F	*p*-value	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value
Left frontal region	Time	2.24	0.140	1.59	0.212	1.82	0.183	7.82	**0.007**	0.06	0.814
	Condition	0.19	0.665	0.21	0.649	1.03	0.315	1.37	0.246	0.20	0.659
	Time × Condition	0.04	0.837	0.26	0.609	0.09	0.764	2.39	0.127	2.55	0.116
Right frontal region	Time	4.64	**0.035**	1.63	0.206	0.09	0.759	0.91	0.344	0.32	0.572
	Condition	3.41	0.070	0.39	0.536	0.06	0.815	0.02	0.888	0.09	0.768
	Time × Condition	1.84	0.180	0.65	0.423	0.24	0.625	0.04	0.842	1.32	0.255
Inter frontal region	Time	7.40	**0.009**	0.03	0.875	2.08	0.155	0.91	0.344	4.27	**0.043**
	Condition	1.34	0.251	3.47	0.068	2.34	0.131	2.06	0.156	0.23	0.634
	Time × Condition	0.01	0.983	0.08	0.782	0.34	0.565	0.86	0.357	0.70	0.406

the post-hoc analysis with Bonferroni's correction. In only the delta band, a significantly increased wPLI over the left-right frontal region was observed ($t = 3.094$, $p = 0.007$; Fig. 4). In addition, there were no changes in frontal asymmetry in delta wPLI in either STIM or SHAM.

4) PHASE-AMPLITUDE COUPLING IN FRONTAL ASYMMETRY

Based on the changes in delta wPLI and alpha PSD after the auditory stimulus, we calculated the MI using the phase of the delta band and the amplitude of the alpha band to investigate the relationship between the delta and alpha bands, as related to frontal asymmetry. However, no significant differences were observed in MI before and after the auditory stimulus, in either left or right frontal regions.

We additionally measured the change in the LI of the MI between delta and alpha pairs to explore the frontal asymmetry of PAC. Only statistically positive LI following the auditory stimulus was shown in STIM ($t = 2.619$, $p = 0.019$; Fig. 5). In other words, frontal asymmetry of associations between delta and alpha pairs does not appear before the auditory stimulus. However, left-hemisphere dominance of relationships in the delta and alpha bands was clearly observed in STIM, not SHAM.

B. CHANGES IN PSYCHOLOGICAL STATE

1) EMOTIONAL STATE QUESTIONNAIRE

To verify BRUMS-32 scores, exploratory factor analysis was used. The KMO measure of sampling adequacy (0.72) and Bartlett's test of sphericity ($chi\text{-}square = 135.55$, $p < 0.001$) were measured. Therefore, there was evidence for unbiased self-reporting in that the KMO measure was higher than 0.70 and Bartlett's test was significant.

Changes in the psychological state were investigated by comparing BRUMS-32 scores before and after the auditory stimulus (Table 3). The "calmness" score significantly increased, whereas "tension," "vigour," and "confusion" scores decreased after STIM. However, increased "fatigue" and decreased "vigour" and "happy" scores were observed in SHAM. When comparing differences in emotional states between the two conditions, "happy" and "calmness" scores in SHAM were significantly decreased compared to STIM.

2) EMOTIONS ACCORDING TO THE VALENCE-AROUSAL MODEL

To categorize participants according to their psychological state after the auditory stimulus, exploratory factor analysis was also used. As a result, two factors were determined for meaningful common factors. The eight scores in BRUMS-32 scores were converted into two factors: valence and arousal.

Fig. 6 shows the results of the exploratory factor analysis of the emotional categories in the valence-arousal coordinate space. Based on participants' BRUMS-32 scores, eight emotional factors were categorized into four basic emotions. Specifically, "tension" is high arousal and negative valence, and "happy" and "vigour" scores are high arousal and

TABLE 3. **Changes in BRUMS-32 scores following the auditory stimulus. Eight factors (mean ± standard deviation) showed a difference in pre- and post-stimulus. The *p*-values less than 0.05 are shown in bold. BRUMS = Brunel mood scale, SD = standard deviation, STIM = stimulation condition, SHAM = sham condition.**

BRUMS-32 score	**STIM**			**SHAM**			**STIM vs. SHAM**		
	Mean (± SD)	*t*-value	*p*-value	Mean (± SD)	*t*-value	*p*-value	Mean (± SD)	*t*-value	*p*-value
Anger	-0.81 (± 2.20)	-1.479	0.160	0.38 (± 2.83)	0.531	0.603	1.89 (± 2.64)	1.800	0.092
Tension	-1.75 (± 2.91)	-2.406	**0.029**	-0.13 (± 2.13)	-0.235	0.817	1.63 (± 3.28)	1.979	0.066
Depression	-1.31 (± 2.80)	-1.876	0.080	-1.31 (± 3.14)	-1.675	0.115	0.01 (± 2.53)	-0.001	0.998
Vigour	-4.13 (± 3.30)	-4.994	**<0.001**	-3.19 (± 3.33)	-3.828	**0.002**	0.94 (± 4.43)	0.846	0.411
Fatigue	1.19 (± 3.47)	1.370	0.191	2.00 (± 2.92)	2.739	**0.015**	0.81 (± 2.64)	1.232	0.237
Confusion	-1.25 (± 2.24)	-2.236	**0.041**	-0.50 (± 2.63)	-0.760	0.459	0.75 (± 2.89)	1.034	0.315
Happy	-0.25 (± 2.46)	-0.406	0.690	-2.31 (± 2.68)	-3.456	**0.004**	-2.06 (± 3.11)	-2.654	**0.018**
Calmness	1.25 (± 2.15)	2.331	**0.034**	-0.63 (± 1.82)	-1.373	0.190	-1.88 (± 2.96)	-2.530	**0.023**

TABLE 4. **Statistical results in pre- and post-stimulus for PSD and wPLI according to the valence-arousal emotion model. Valence is divided into positive and negative groups, and arousal is divided into high and low groups. The *p*-values less than 0.05 are shown in bold. PSD = power spectral density, wPLI = weighted phase lag index.**

Method	**Region**	**Positive valence**		**Negative valence**		**High arousal**		**Low arousal**	
		chi-square	*p-value*	*chi-square*	*p-value*	*chi-square*	*p-value*	*chi-square*	*p-value*
PSD	Left frontal region	-10.56	**0.001**	-2.64	0.104	-3.73	0.054	-7.15	**0.007**
	Right frontal region	-2.35	0.126	-4.28	**0.039**	-0.93	0.334	-7.15	**0.007**
wPLI	Left frontal region	1.57	0.210	2.64	0.104	2.92	0.088	1.59	0.207
	Right frontal region	1.14	0.286	3.14	0.076	0.55	0.458	3.45	0.063
	Inter frontal region	4.37	**0.037**	4.28	**0.039**	1.99	0.158	4.32	**0.038**

positive valence. "Calmness" is low arousal and positive valence. Finally, "anger," "confusion," "depression," and "fatigue" scores are low arousal and negative valences. As a result, according to the valence dimension, all 16 participants were subgrouped into 11 participants with positive valence and 5 participants with a negative valence. In addition, according to the arousal dimension, participants were subgrouped as 8 participants with high arousal and 8 participants with low arousal.

C. CHANGES IN EEG ACCORDING TO EMOTIONAL STATE

We investigated changes in frontal regions according to emotions (valence and arousal) for the same auditory stimulus based on factor analysis. In particular, we focused on significant changes in alpha power and delta wPLI after the auditory stimulus.

1) SPECTRAL POWER IN FRONTAL ASYMMETRY AFTER THE AUDITORY STIMULUS

In both the valence and arousal groups, there were significant differences in alpha power (Table 4). For valence, alpha power post-stimulus was decreased compared to that pre-stimulus in the positive and negative groups over the left ($t = -3.409$, $p = 0.005$) and right frontal regions ($t = -5.701$, $p = 0.001$; Fig. 7(a)). Similarly, in arousal, there was reduced alpha power post-stimulus in only the low-arousal group in the left ($t = -5.071$, $p = 0.003$) and right frontal regions ($t = -6.076$, $p = 0.001$; Fig. 7(b)).

To compare alpha power before and after the stimulus between left and right frontal regions for frontal asymmetry, significant changes in negative valence were observed ($t = -1.885$, $p < 0.001$), but no statistical differences were found in positive valence ($t = -0.318$, $p = 0.716$). In the arousal group, there were no statistical differences between left and right frontal regions (high arousal: $t = -0.573$, $p = 0.561$; low arousal: $t = -1.193$, $p = 0.369$).

2) FUNCTIONAL CONNECTIVITY IN FRONTAL ASYMMETRY AFTER THE AUDITORY STIMULUS

We compared the change in delta wPLI for each valence and arousal group. There were only differences in delta wPLI over the inter (left-right) frontal region (Table 4). Fig. 8 shows

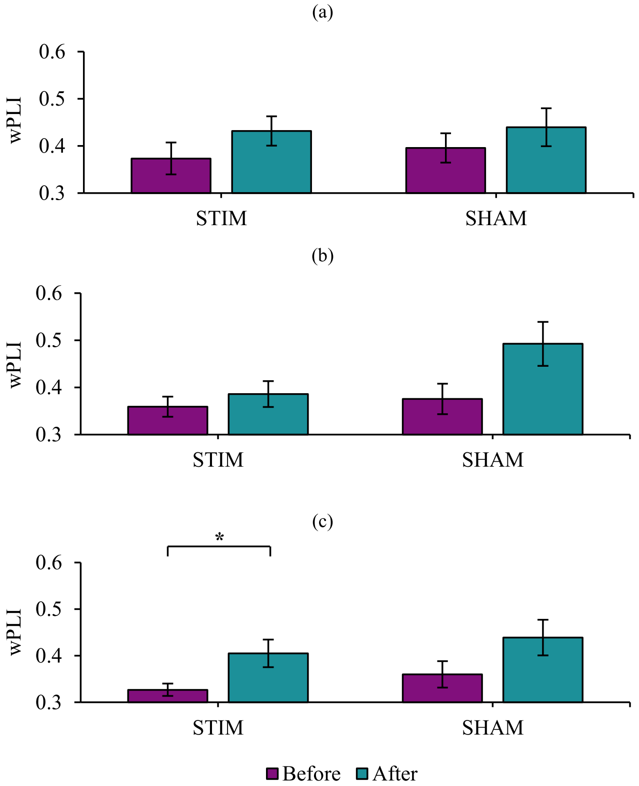

FIGURE 4. Changes in delta wPLI post-stimulus in frontal regions. Delta wPLI on the (a) left, (b) right, and (c) inter (left-right) frontal regions was calculated for both STIM and SHAM. Error bars show standard errors. wPLI = weighted phase lag index, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

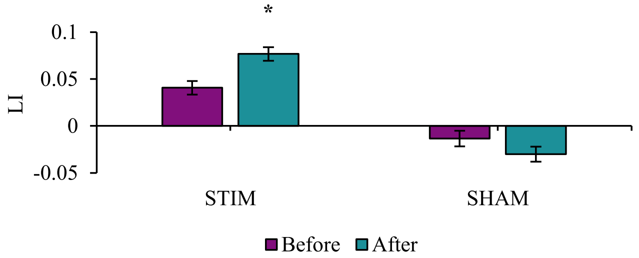

FIGURE 5. Changes of the LI of the MI in pre- and post-stimulus. MI was calculated using phase in the delta band and amplitude of the alpha band over the frontal region. Then, LI was measured to investigate the frontal asymmetry of the MI. Error bars show standard errors. LI = laterality index, MI = modulation index, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

the increased wPLI between left-right regions after the auditory stimulus in only the positive-valence group ($t = 2.516$, $p = 0.007$) and the low-arousal group ($t = 2.386, p = 0.007$).

For frontal asymmetry, we additionally compared the difference in delta wPLI before and after the stimulus between left and right frontal regions. There were no significant differences in delta wPLI between left and right regions in any valence or arousal group (positive valence: $t = -0.807$, $p = 0.463$; negative valence: $t = 0.363$, $p = 0.834$; high arousal: $t = -0.735, p = 0.435$; low arousal: $t = -0.116, p = 0.882$).

3) PHASE-AMPLITUDE COUPLING IN FRONTAL ASYMMETRY

Depending on the emotional states, we investigated MI between delta and alpha bands after the auditory stimulus. There were no significant differences in MI for delta-alpha PAC before and after the auditory stimulus in either the left or right frontal region.

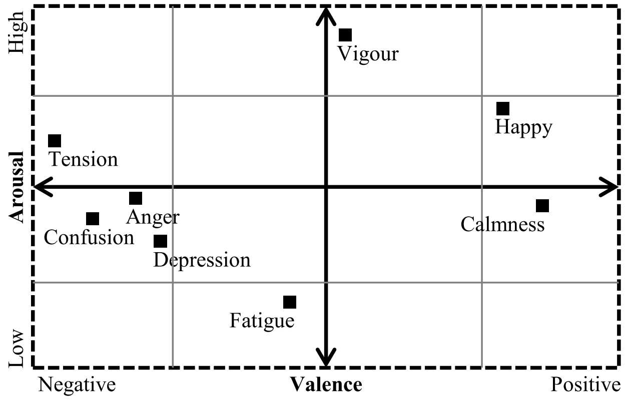

FIGURE 6. 2D emotion model by valence and arousal in the BRUMS-32 questionnaire. The horizontal axis represents the valence dimension (positive or negative) and the vertical axis represents the arousal dimension (high or low). BRUMS = Brunel Mood Scale.

We observed a change in the LI value of MI in delta and alpha pairs after the auditory stimulus for frontal asymmetry (Fig. 9). In valence, only the positive group had a significantly positive LI between delta and alpha pairs after the auditory stimulus ($t = 3.399, p = 0.003$). However, there was a positive LI in delta and alpha bands after the auditory stimulus for only the low-arousal group ($t = 4.896$, $p < 0.001$). In summary, after the auditory stimulus, there was a clear left frontal dominance for relationships between delta and alpha frequency bands only in those who felt positive valence and low arousal about natural sounds.

V. DISCUSSION

In this study, we aimed to investigate the differences in frontal EEG asymmetry of emotion following an auditory stimulus. During the auditory stimulus, alpha power was significantly reduced compared to baseline. However, there was no statistical change in wPLI during the 10-min auditory stimulus for all frequency bands. After the auditory stimulus, alpha power was decreased in both left and right frontal regions. However, no significant differences in alpha power between the left and right regions were observed. In other words, frontal asymmetry was not observed after auditory stimuli. Similarly, delta wPLI over the left-right (inter) frontal regions was increased after the auditory stimuli compared to baseline, but there was no frontal EEG asymmetry related to wPLI. For MI between delta and alpha pairs, left-hemisphere dominance appeared after the auditory stimulus. Based on the BRUMS-32 questionnaire, factor analysis was used to categorize participants based on emotion. As a result, frontal asymmetry of alpha power was clearly observed in the negative valence group. In addition, changes in alpha power and delta wPLI differed depending on the levels of valence and arousal of emotions after the auditory stimulus.

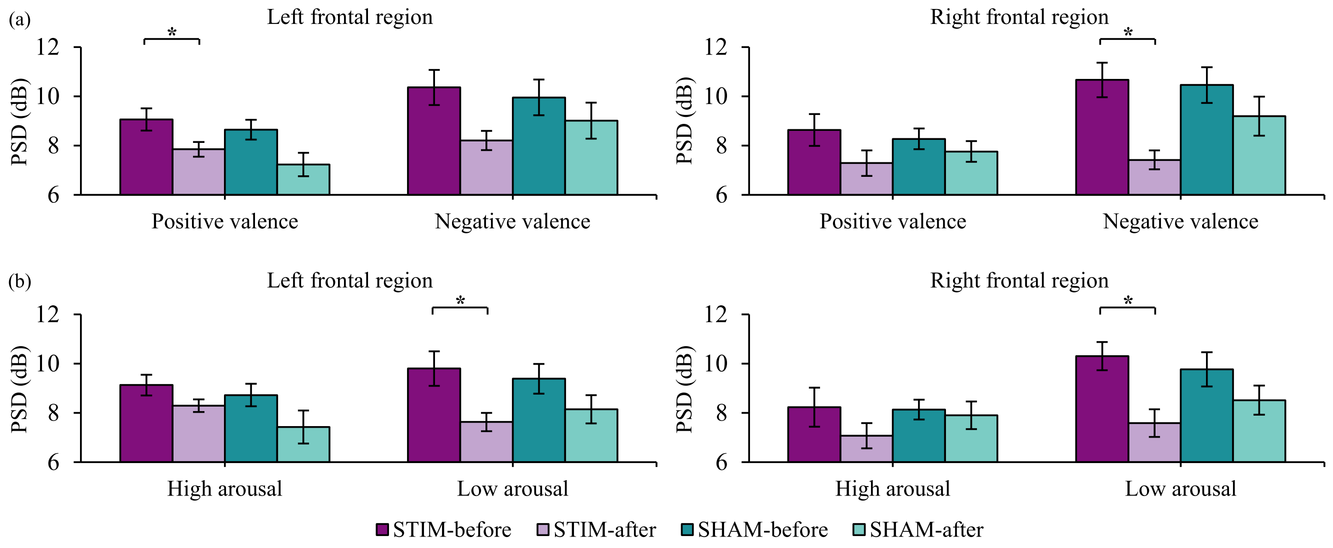

FIGURE 7. Changes in alpha power post-stimulus according to the emotional state. Regarding the 2D emotion model, changes in alpha power were identified in (a) and (b) arousal groups. Valence is divided into positive and negative, while arousal is divided into high and low. Error bars show standard errors. PSD = power spectral density, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

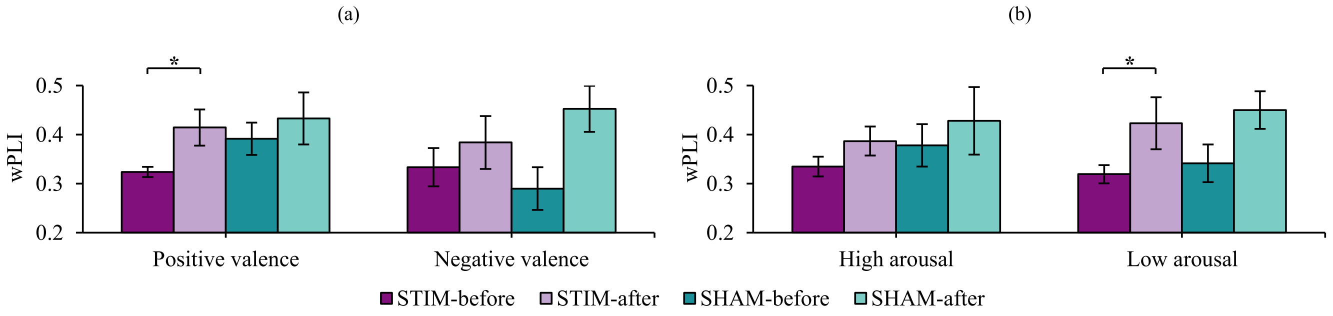

FIGURE 8. Changes in delta wPLI over the inter-frontal region post-stimulus according to emotional state. Regarding the 2D emotion model, changes in wPLI were identified in the (a) valence and (b) arousal groups. Valence is divided into positive and negative, while arousal is divided into high and low. Error bars show standard errors. wPLI = weighted phase lag index, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

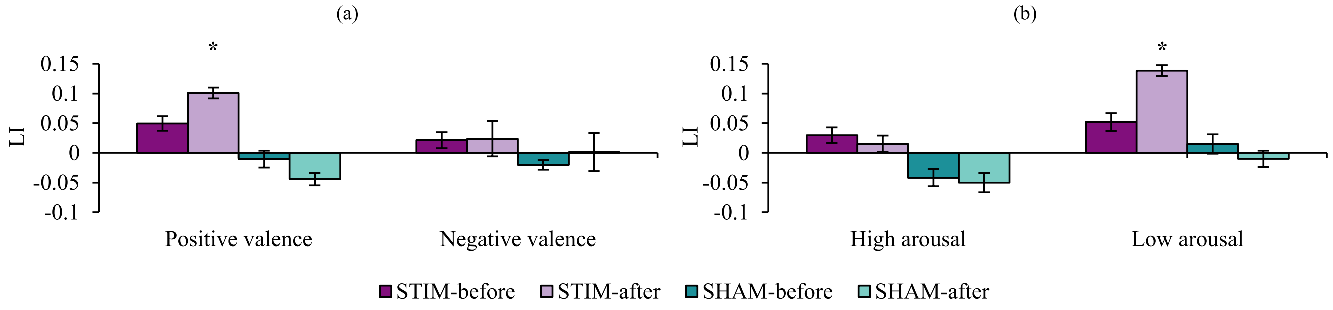

FIGURE 9. Changes in the LI of the MI after the stimulus according to the emotional state. MI was calculated using the phase in the delta band and the amplitude of the alpha band over frontal regions. Then, LI was measured to investigate frontal asymmetry of the MI. Regarding the 2D emotion model, changes in LI were identified in the (a) valence and (b) arousal groups. Valence is divided into positive and negative, while arousal is divided into high and low. Error bars show standard errors. LI = laterality index, MI = modulation index, STIM = stimulation condition, SHAM = sham condition, * < 0.05 with Bonferroni's correction.

We observed reduced alpha power over all brain regions during the auditory stimulus. Some studies showed a decrease in alpha power not only with natural sounds but also when binaural beats that induce theta power were played [50]. The auditory pathway extends through the parietal region, including the temporal region located in the primary auditory cortex, and eventually to the prefrontal and frontal regions through serial and parallel processing of sensory information [75]. Thus, it seems plausible that changes occur in all brain regions whilst listening to auditory stimulus.

According to the BRUMS-32 scores, STIM was clearly associated with an increase in positive emotion (''calmness'') and a decrease in negative emotions (''tension'' and ''confusion''). In addition, positive emotions (''happy'' and ''calmness'') in STIM were higher than they were in SHAM, and SHAM was clearly associated with an increase in negative emotion (''fatigue'') and a decrease in positive emotion (''happy''). Traditionally, it is thought that listening to natural sounds makes people feel better and more psychologically stable [33]. However, the same natural sound can evoke different emotions in different people. As a result of factor analysis using BRUMS-32 scores, the eight emotions were converted into a two-dimensional valence and arousal model. This was similar to the conventional emotional model [76].

Following the auditory stimulus, alpha power decreased in both left and right frontal regions. However, we did not observe any frontal asymmetry. Interestingly, after being divided into two groups based on emotions, frontal EEG asymmetry in alpha power between the left and right regions was clear. Specifically, there were significant differences in alpha power between the left and right frontal regions only in the negative valence group. This result supports the idea that alpha asymmetry in frontal regions is associated with emotions [17], [47]. Alpha activity plays a major role in relation to the emotional process [15]. In line with previous studies, we found reduced alpha power after the auditory stimulus. An alpha asymmetry reflects the course of the cognitive processes by indexing frontal cortex function [77]. Some studies have reported that alpha power in left frontal regions decreases when people listen to positive music, but that alpha power in right frontal regions decreases when listening to negative music [16]. In fact, a decrease in alpha power in positive and negative emotions is associated with left and right frontal regions, respectively [30], [78]. In this regard, the alpha band in the left and right frontal regions plays a different role in relation to emotions. According to the asymmetric inhibition model, a mechanism in the left frontal cortex suppresses negative distractors [31] and a mechanism in the right frontal cortex suppresses positive distractors. In other words, the left hemisphere mainly processes positive emotions, whereas the right hemisphere mostly processes negative emotions [25]. Therefore, in alpha activity, left frontal regions might predict emotional flexibility and regulation, whereas right frontal regions might predict affective disorders such as depression and social anxiety disorder [28].

We also observed increased delta wPLI only over the inter (left-right) frontal region. This characteristic was particularly noticeable in the positive valence group. Delta coherence increases with cognitive load [79] and reflects the emotion regulation process [34]; this characteristic of delta connectivity may be relevant to changes in emotion. In addition, in line with our results, there is a positive correlation between valence and frontal inter-hemispheric flow [80]. This interconnectivity is believed to transmit information so that both hemispheres, which play different roles in relation to frontal asymmetry, can interact with each other. Our results show that ''vigour'' and ''fatigue'' appear to be the critical emotional states responsible for high and low arousal, respectively. Alpha power decreased significantly in both the left and right frontal regions. Previous studies showed that a persistent auditory stimulus can cause mental fatigue and decreased alpha power in frontal regions [81], [82]. In addition, delta power increased, but alpha power decreased, during mental fatigue [83]. We also found that delta wPLI increased only in the low arousal group following auditory stimuli. In line with our findings, delta connectivity, which is highly related to sleep and unconscious states, is enhanced during fatigue (low arousal) in frontal regions [84].

Alpha power and delta wPLI are important factors in relation to the frontal asymmetry of emotions. Therefore, we chose delta phase dynamics and an alpha amplitude to explore the relationship between the delta and alpha bands. In the auditory cortex, delta phase is responsible for modulating cortical excitability and for inhibiting alpha oscillations in the cortex. Indeed, the role of these delta phases was unchanged before and after auditory stimuli [42], [85]. However, we observed no significant changes in MI between delta and alpha pairs after auditory stimuli. Delta wPLI and alpha power appear to change without much impact from each other following auditory stimuli. Nevertheless, there was a clear left frontal dominance for relationships between delta and alpha pairs only in the STIM after the auditory stimulus. Indeed, the dominance of the left and right hemispheres depends on the stimulus. The left and right hemispheres are more active with positive and negative stimuli, respectively. Specifically, left frontal regions process the experience of positive feelings (e.g., cheerfulness and ecstasy), whereas right frontal regions process the experience of the reverse emotions (e.g., anxiety and sorrow) [86]. Therefore, left dominance is not surprising given that natural sounds are likely to generate positive stimulation.

This study has some limitations. First, only natural sounds that are usually thought to have a positive impact were used in this study. Negative or neutral sounds should be added in further studies. Second, we observed changes only in delta wPLI and alpha power post-stimulus. In previous studies, other frequency changes have often been found. This is probably because a natural sound itself acts as a positive factor, and the associated changes were more prominently noted. Third, only wPLI was calculated to investigate the brain connectivity in this study. However, further studies on effective connectivity are necessary to explore the mechanisms related to emotions more precisely.

VI. CONCLUSION

Can we be certain that individuals feel positive emotions just because positive stimuli are presented? We considered this question and investigated the brain changes based on emotions measured by a psychological survey when all individuals were presented with the same positive stimulus. As a result, only people who experienced negative valence after listening to natural sounds clearly showed an alpha frontal asymmetry. We also observed left frontal dominance for the PAC when exploring the relationship between delta and alpha bands. These results support the idea that frontal asymmetry is associated with emotional mechanisms, which can also help treat or predict emotional diseases such as anxiety. In addition, these findings can be used to improve emotion recognition performance by presenting new features. It could be utilized directly for entertainment, education, the brain-computer interface in real-world practical applications.

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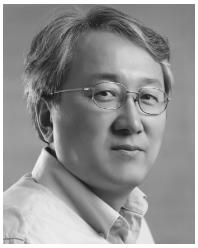

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