

Neurophysiological Response Based on Auditory Sense for Brain Modulation Using Monaural Beat

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Abstract—Brain modulation is a modification process of brain activity through external stimulations. However, which condition can induce the activation is still unclear. Therefore, we aimed to identify brain activation conditions using 40 Hz monaural beat (MB). Under this stimulation, auditory sense status which is determined by frequency and power range is the condition to consider. Hence, we designed five sessions to compare; no stimulation, audible (AB), inaudible in frequency, inaudible in power, and inaudible in frequency and power. Ten healthy participants underwent each stimulation session for ten minutes with electroencephalogram (EEG) recording. For analysis, we calculated the power spectral density (PSD) of EEG for each session and compared them in frequency, time, and five brain regions. As a result, we observed the prominent power peak at 40 Hz in only AB. The induced EEG amplitude increase started at one minute and increased until the end of the session. These results of AB had significant differences in frontal, central, temporal, parietal, and occipital regions compared to other stimulations. From the statistical analysis, the PSD of the right temporal region was significantly higher than the left. We figure out the role that the auditory sense is important to lead brain activation. These findings help to understand the neurophysiological principle and effects of auditory stimulation.

Keywords—brain modulation, monaural beat, sense, electroencephalogram

I. INTRODUCTION

Brain modulation aims to induce brain activity using various stimulations. Transcranial electric and magnetic stimulation are one of the various methods of brain modulation [1], [2]. But these methods have adverse effects that contain mild tingling sensation, fatigue, and headache [3].

Unlike these direct transcranial-based stimulations, binaural beat (BB) and monaural beat (MB) are indirect auditory-based stimulations [4], [5]. These beats consist of lower and upper frequencies called the carrier and offset [6]. The BB is a stereo sound using sine waves of neighboring frequencies into each ear, whereas the MB is a mono sound that combines into one channel [6], [7]. These auditory-based stimulations can induce the activation of brain signals based on the differences in the carrier and offset frequencies, which can be monitored by the frequency-following response (FFR) [8].

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Moreover, these do not need any direct device to the scalp, just earphones or speakers.

Auditory stimulation like BB and MB are recognized by the auditory sense which is a simple automatic reaction to sounds by an auditory organ. It is different than perception which needs more complex and requires effort for meaningful interpretations of experiences [9]. When people are subjected to stimulation by BB and MB, they can sense the integrated sound of carrier and offset frequency, but they can not perceive that the sound is a combination of two different frequencies [10]. Also, whether or not auditory sensation is possible in these stimulations is determined by the frequency and power range [11]. If the frequency is higher than the hearing threshold or the power is smaller than the threshold, people can not sense the BB and MB. Most studies observed the effect of auditory stimulations which could sense [12]. However, these could not consider inaudible stimulation that could not sense.

In this study, we aimed to find the activation condition of auditory stimulation in terms of auditory sense. In detail, MB was used as auditory stimulation to confirm the changes in EEG amplitude clearly. Moreover, we designed the experiment to compare the outcomes in participants after subjecting them to both audible and inaudible conditions, considering both frequency and power range. In consequence, we could identify that the auditory sensation has an essential role in inducing brain activity.

II. METHODS

A. Participants and Experimental Procedure

Ten participants were included in this study (five males and five females, mean ages 26.1 ± 3.4 years). None of the participants had a medical history of claustrophobia or hearing loss. This study was approved by the Institutional Review Board at Korea University (KUIRB-2022-0222-01), and each participant provided written informed consent before the start of experiment.

The participants visited the soundproof booth and prepared for electroencephalogram (EEG) acquisition (Fig. 1-a). Individual hearing thresholds were measured (mean hearing downer threshold 9.5 ± 3.3 dB) and five sessions with different stimulation conditions were performed randomly. Each session consisted of two minutes of rest and ten minutes of stimulation. It is known as the optimal time to activate the brain [6], [13]. During the experiments, the participants kept their eyes closed (Fig. 1-b).

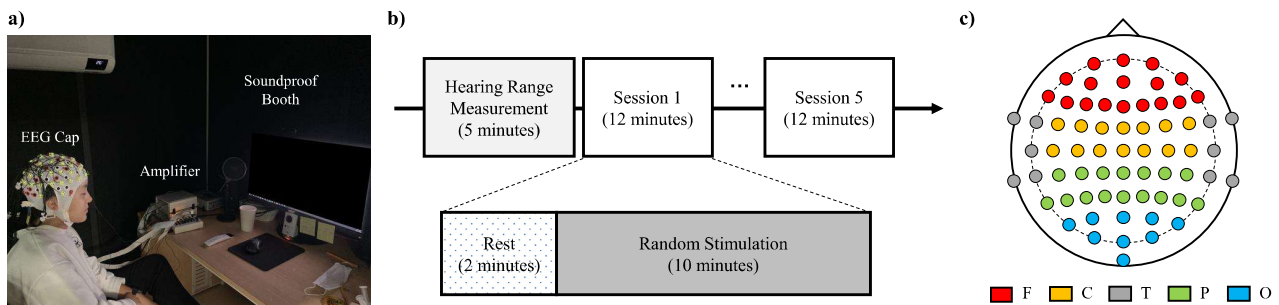


Fig. 1. Experimental setting. a) Experimental environment. b) Experimental procedure. Random stimulation consists of no stimulation, audible monaural beat, inaudible monaural beat in frequency, inaudible monaural beat in power, and inaudible monaural beat in frequency and power. c) Segmentation of brain regions. The brain region is divided into five groups: F=frontal, C=central, T=temporal, P=parietal, O=occipital.

B. Audible and Inaudible Monaural Beat

The MB, which has a greater amplitude and a broader frequency range than the BB, was used in the experiment [4]. The targeted frequency was set to 40 Hz which has a more significant auditory potential response than different frequencies [14]. We presented the no stimulation and four conditions of the 40 Hz MB: no stimulation (NS), audible (AB), inaudible in frequency (IB-f), inaudible in power (IB-p), and inaudible in frequency and power (IB). For the AB, we set the carrier tone to 400 Hz which performs better than other frequencies and the offset tone of stimulation to 440 Hz [15]. The sound intensity was set to 40 dB to activate the auditory cortex [16]. For IB-f, the carrier frequency was 18,000 Hz and the offset was 18,040 Hz, which falls within an inaudible range for humans [11]. The power was the same as that used for AB. For IB-p, we set the power to 5 dB based on the fact that we tested a hearing threshold. The frequency was the same as the audible condition. For IB, we combined the frequency setting of IB-f and the power setting of IB-p. All stimulations were created using the audio generator program Gnaural 1.0.20110606.

C. EEG Recording and Analysis

We recorded the EEG signal at a 1,000 Hz sampling rate using an amplifier (BrainAmp; Brian Products, Germany). The 64 channels, using Ag/AgCl electrodes, were placed according to the 10-20 international system. EEG pre-processing was performed with the EEGLAB toolbox for MATLAB following [17], [18] and consisted of down-sampled to 250 Hz, band pass filtered between 0.5 Hz to 50 Hz, and channel interpolation using the Gaussian distributions kurtosis.

The recorded EEG signals were segmented into one minute intervals to observe changes over time. Additionally, we divided brain regions into five groups as follows: frontal, central, temporal, parietal, and occipital regions (Fig. 1-c) [18]. To identify brain symmetry, each region was divided into left and right, excluding the center electrodes (FPz, AFz, Fz, FCz, Cz, CPz, Pz, POz, Oz, and Iz).

For neurophysiological analysis, the power spectral density (PSD) was estimated using a fast Fourier transform. The

power ratio (R_f) was calculated to identify the trend changes in PSD for each frequency and defined as

$$R_f = \frac{2 \times PSD_f}{PSD_{f-1} + PSD_{f+1}}, \quad (1)$$

where the frequency (f) for the analysis was set from the 1 Hz to 50 Hz range. In the case of a constant tendency, R_f converges to one, otherwise, it diverges to infinity.

All data were analyzed using one-way analysis of variance (ANOVA) method [19]. In the case of significance, a post-hoc analysis was performed using t -test. The significance level was set at $p < 0.05$.

III. RESULTS

A. Frequency-following Response by Stimulation

Fig. 2 shows the power ratio near the targeted frequency (40 Hz) to identify the EEG amplitude changes caused by the stimulation. We observed a considerably increased response at 40 Hz in only one of the sessions, AB (NS: $R_{40}=1.07$, AB: $R_{40}=10.11$, IB-f: $R_{40}=0.83$, IB-p: $R_{40}=0.94$, IB: $R_{40}=1.04$) with significance (NS: $p=0.01$, IB-f: $p=0.01$, IB-p: $p=0.01$, IB: $p=0.01$). In comparison, a significantly smaller change in response was observed at 39 Hz and 41 Hz for AB ($p < 0.001$, each). In other stimulations, including NS and inaudible conditions, there were no negative or positive peaks at 40 Hz (NS vs. IB-f: $p=0.07$, NS vs. IB-p: $p=0.42$, NS vs. IB: $p=0.83$, IB-f vs. IB-p: $p=0.29$, IB-f vs. IB: $p=0.15$, IB-p vs. IB: $p=0.35$). We also explored the constant tendency in other frequencies excluding 40 Hz in all sessions and none of the sessions showed any differences.

Fig. 3 shows the results of time-related spectral analysis at 40 Hz of the segmented stimulation phase. Baseline values (before stimulation) were essentially similar among the five experimental groups. However, in the stimulation phase, we observed a statistically significant power peak during AB compared with other stimulations ($p < 0.001$, each time segment). During the first minute, activation of the targeted frequency in AB group was significantly higher than in IB-f and IB-p, while it was only slightly higher compared to other two groups (NS: $p=0.09$, IB-f: $p < 0.01$, IB-p: $p < 0.01$, IB: $p=0.06$), however, it increased significantly compared to

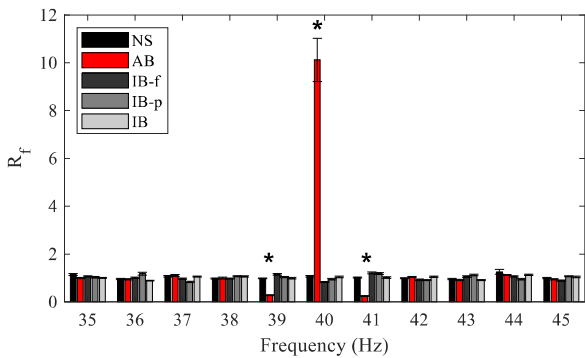


Fig. 2. Power ratio nearby targeted frequency (40 Hz). R_f =Power ratio, NS=no stimulation, AB=audible monaural beat, IB-f=inaudible monaural beat in frequency, IB-p=inaudible monaural beat in power, IB=inaudible monaural beat in frequency and power. The error bars indicate standard errors. * represents the statistical significance ($p < 0.05$).

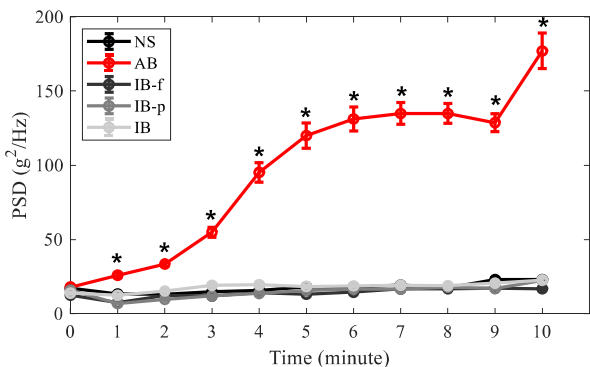


Fig. 3. Power spectral density (PSD) from 40 Hz for ten minutes stimulation phase in each stimulation. NS=no stimulation, AB=audible monaural beat, IB-f=inaudible monaural beat in frequency, IB-p=inaudible monaural beat in power, IB=inaudible monaural beat in frequency and power. The error bars indicate standard errors. * represents the statistical significance ($p < 0.05$).

other stimulations until the end of the phase ($p < 0.05$, each). No difference was observed between the NS and inaudible conditions.

Moreover, we compared the PSD changes at 40 Hz. Fig. 4 shows the topology of the t -value of the comparison between NS and the other stimulations. We observed significant activation of some of channels in the parietal, temporal, and occipital regions in AB. However, there were no differences between the other sessions and NS.

B. Asymmetric activation by stimulation

We compared the PSD changes at 40 Hz in all brain regions (Table. I). There was no statistically significant difference, for any regions, between the other four groups, excluding AB. However, significantly larger PSD values were obtained for AB compared to the other stimulation groups. In detail, for the frontal region, there was a difference only between AB and IB-f, not others (NS: $p=0.05$, IB-f: $p=0.02$, IB-p: $p=0.1$, IB: $p=0.09$). Additionally, for the central region, AB group had more pronounced activation

TABLE I
COMPARISON OF POWER SPECTRAL DENSITY FROM 40 HZ BETWEEN STIMULATIONS.

Region	NS	AB	IB-f	IB-p	IB	p -value
Frontal	25.93	55.88	20.56	28.31	27.13	0.01
Central	114.76	526.26	42.82	70.01	96.18	<0.001
Temporal	14.34	34.21	9.86	10.80	12.22	<0.001
Parietal	30.52	200.47	24.73	27.82	36.86	<0.001
Occipital	95.40	620.33	104.70	91.34	118.79	<0.001

AB=audible monaural beat, IB-f=inaudible monaural beat in frequency, IB-p=inaudible monaural beat in power, IB=inaudible monaural beat in frequency and power. We marked the statistical significance in bold.

TABLE II
COMPARISON OF POWER SPECTRAL DENSITY FROM 40 HZ BETWEEN RIGHT AND LEFT BRAIN IN AUDIBLE MONAURAL BEAT.

Region	Right	Left	p -value
Frontal	83.53	64.36	0.19
Central	61.84	39.46	0.16
Temporal	670.30	432.50	0.02
Parietal	278.74	180.60	0.07
Occipital	686.55	511.88	0.13

We marked the statistical significance in bold.

than the others four groups (NS: $p=0.01$, IB-f: $p=0.003$, IB-p: $p=0.01$, IB: $p=0.01$). The inducing effect of AB in the temporal region was also significant (NS: $p=0.01$, IB-f: $p=0.002$, IB-p: $p=0.004$, IB: $p=0.01$). In the parietal region, differences between AB and other groups were statistically significant (NS: $p=0.002$, IB-f: $p=0.001$, IB-p: $p=0.001$, IB: $p=0.002$). Similar results were obtained for the occipital region (NS: $p=0.001$, IB-f: $p < 0.001$, IB-p: $p=0.002$, IB: $p=0.002$).

We also carried out a brain symmetry comparison between left and right brain regions (Table. II). The PSD was only calculated for AB group as only this group showed targeted brain activity after stimulation. The brain response was symmetrical in the frontal, central, parietal, and occipital regions. However, in the temporal region, the right brain was significantly more activated compared to the left brain.

IV. DISCUSSION AND CONCLUSION

This study investigated the relationship between auditory senses and brain activation, especially FFR. We compared the audible and inaudible conditions and observed that only AB could significantly induce brain activity at 40 Hz. Additionally, its effects increased over stimulation time and were slightly more extensive in the right brain.

Our results showed that AB caused FFR in all brain regions, and the right temporal region was more activated than other regions throughout the stimulation time. This result is in agreement with the brain activation tendencies that use BB or MB [12], [16]. Exceptionally, in the power ratio analysis in this study, there were two additional significantly different points. However, this phenomenon occurred because a prominent power peak at 40 Hz affected the ratio formula of the two sides and, not because of any change in

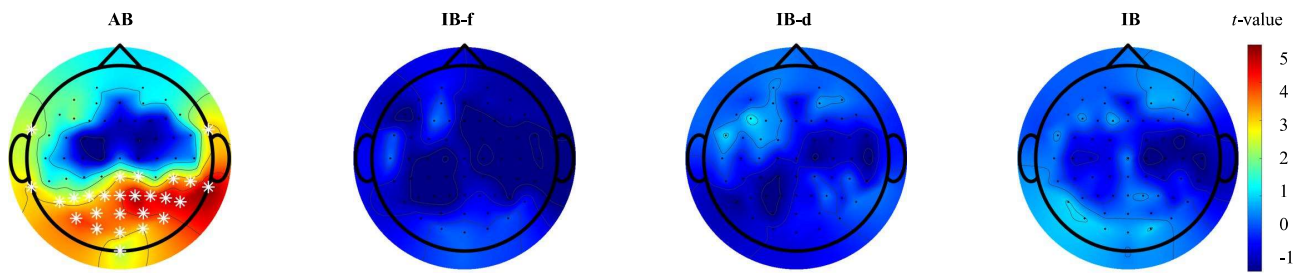


Fig. 4. Topographical distribution of the t -value of the comparison from 40 Hz power spectral density between no stimulation (NS) and other sessions: audible monaural beat (AB), inaudible monaural beat in frequency (IB-f), inaudible monaural beat in power (IB-p), inaudible monaural beat in frequency and power (IB). * represents the statistical significance ($p < 0.05$).

brain activity. A comparison of PSD between right and left regions was also in accordance with the results of previous studies [8]. These studies used auditory click stimulation and observed activation from the right auditory cortex. Therefore, only AB caused targeted FFR in all brain regions, and a right-asymmetric effect was observed for the temporal region.

Unlike AB, we could not find an increasing or decreasing tendency in the amplitude during exposure to inaudible MBs. The MB is known to have a more comprehensive carrier frequency range than the BB and a recent study compared its effectiveness up to 3,000 Hz [4], [15]. We explored the utilization of MB over 3,000 Hz in extension. In terms of inaudible powers, to the best of our knowledge, no previous study has carried out such a comparison, and ours is the first study of this kind. Since inaudible MBs didn't involve any sound processing in the brain, our results provided evidence that FFR is a by-product of sound processing.

In conclusion, we investigated the role of auditory senses in brain activation in response to MB. The auditory sense in terms of frequency and power is essential to lead brain activation. Our study could help to understand the principle of FFR by auditory stimulation. In addition, these findings should be considered important in various fields of brain modulation using MB, such as clinical treatment, education, sleep technology, and brain-computer interfaces [20].

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