Magnetoencephalographic activities related to the magnitude of the interaural cross-correlation function (IACC) of sound fields

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Magnetoencephalographic (MEG) responses to the magnitude of the interaural cross-correlation function (IACC) of a sound field were investigated. The source signal was the word "piano", which had a 0.35-s duration. In MEG measurements, combinations of a reference stimulus (IACC = 1.0) and test stimuli (IACC = 0.27, 0.61, and 0.90) were presented 50 times alternately at a constant 1.5-s interstimulus interval. The MEG responses evoked by each stimulus in the pair were integrated and recorded with a 122-channel whole-head neuromagnetometer and analyzed using an autocorrelation function (ACF) and a cross-correlation function (CCF). The results showed that the effective duration of ACF, τ_e, and the maximum value of CCF, $|\phi(\tau)|_{max}$, of MEG between 8-13 Hz become larger as the IACC decrease. Although subjective preference tests for the IACC of speech sound fields have not been conducted in the present study, the previous studies of subjective preference for sound fields have showed that lower IACC is preferred. Therefore the results indicate that the brain repeats a similar temporal rhythm over a wider area under preferred sound fields.

Keywords: autocorrelation function (ACF), cross-correlation function (CCF), magnetoencephalography (MEG), magnitude of interaural cross-correlation function (IACC)

1. INTRODUCTION

In the field of room acoustics, four orthogonal physical parameters influencing subjective preference for sound fields have been reported: (1) listening level (LL), (2) delay time of a single reflection in reference to the direct sound, (Δt_1), (3) subsequent reverberation time (T_{sub}), and (4) the magnitude of the interaural cross-correlation (IACC) [1-3]. To investigate the relationship between brain activities and subjective preferences for sound fields, Ando and Chen [4], Chen and Ando [5] and Sato et al. [6] analyzed electroencephalography (EEG) with the autocorrelation function (ACF). The EEG frequency band between 8 and 13 Hz was analyzed by the effective duration of the envelope of the normalized ACF (τ_e) when the factors of sound fields, Δt_1, T_{sub} and IACC were varied. The results showed that the τ_e of the EEG between 8-13 Hz was significantly longer for the preferred conditions of these factors, Δt_1, T_{sub} and IACC. It has recently been reported that a τ_e of a MEG between 8-13 Hz is strongly correlated with subjective preference for Δt_1 of speech [7]. τ_e is defined as the time taken for the ACF envelope to reduce to ten percent of its original value, representing repetitive features within the signal itself. It has recently been found that the maximum amplitude of the cross-correlation function (CCF). $|\phi(\tau)|_{max}$ of a MEG between 8-13 Hz is correlated with subjective preference for the Δt_1 of speech [8]. ACF analysis concentrates on the intra-channel correlations, while CCF analysis concentrates on inter-channel correlations in the time domain.

The purpose of this study was to examine the effects of the IACC on MEG responses when the sound source was speech. In previous studies on the relationship between brain activities and subjective preference for sound fields, the sound source was a music motif and only the EEG or MEG frequency band between 8-13 Hz was analyzed. Here, speech was used as the sound source and other MEG frequency bands were also analyzed by the ACF and CCF.

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2. METHODS

2.1. IACC of sound fields

The interaural cross-correlation function (IACF) between two sound signals at both ears $f_l(t)$ and $f_r(t)$ is defined by

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_{-T}^{+T} f_l'(t)\, f_r'(t+\tau)dt \qquad (1)$$

where $f_l'(t)$ and $f_r'(t)$ are obtained after passing through the A-weighted network, which approximately corresponds to ear sensitivity [3]. The normalized IACF is defined by

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}} \qquad (2)$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the ACFs at $\tau = 0$ for the left and right ear, respectively. The IACC is defined by the possible maximum interaural time delay, say, $|\tau| < 1.0$ ms.

The speech signal used in this study was the word "piano" enunciated by a female voice of 0.35 s duration recorded in an anechoic room. A detailed account of the method of controlling IACC procedures have been presented earlier [6, 9]. The stimuli used in the MEG experiment were picked up using a dummy head in an anechoic room. Two symmetrical lateral reflections with a horizontal angle $\xi = \pm 54^o$ added to the frontal direct sound ($\xi = 0^o$) were produced in an anechoic room. The distance between the loudspeakers and the center of the dummy head was 1.00±0.01 m. The loudspeakers were at the same horizontal level as the ears of the dummy head. To produce incoherent conditions, the time delays between the direct sound and the two reflections were fixed at Δt_1 = 20 ms and Δt_1 = 38 ms. In order to control the IACC under the condition of fixing the listening level, the amplitudes of the direct sound (A1) and two lateral reflections (A2) were adjusted by its ratio. The measured IACCs, for the integration interval 2T = 0.35 s, were 0.90, 0.61 and 0.27. The amplitudes of two reflections (A2) relative to the amplitudes of the direct sound (A1) were -20, -8 and -2 [dB]. The interaural level difference was 0 dB and there was no interaural delay between the left and right signals, i.e., the maximum of the IACC was always at t = 0.

2.2. Recordings of MEG responses

Ten 21-to 34-year-old subjects with normal hearing participated in the experiment. The MEG responses were measured in a magnetically shielded room and recorded (pass-band 0.03-100 Hz, sampling rate 400 Hz) with a 122-channel whole-head magnetometer (Neuromag-122™, Neuromag Ltd., Finland) [10]. The binaural sound signals recorded through the dummy head in an anechoic room were delivered to subjects through plastic tubes and inserted earpieces at a comfortable listening level of approximately 70 dB, A-weighted, adjusted separately for each subject. The binaural sound signals used in MEG experiment were measured with an ear simulator, including a microphone and a preamplifier, and an adaptor connected to the earpiece. The reconfirmed IACCs of the stimuli, for the integration interval 2T = 0.35 s, were 0.90, 0.61 and 0.27. Combinations of a reference stimulus (IACC = 1.0) and test stimuli (IACC = 0.90, 0.61 and 0.27) were presented alternately 50 times at a constant 1.5 s interstimulus interval and the MEGs were measured. During measurements, the subjects sat in a chair and were asked to close their eyes to fully concentrate on the sound. The recorded data were digitally bandpass-filtered in the following frequency bands: 4-8, 8-13, 13-30, and 30-50 Hz in order to analyze them separately. Each response, corresponding to one stimulus, was analyzed by ACF and CCF for each subject. Figure 1 shows an example of a recorded MEG between 8-13 Hz. We defined five parts, frontal, vertex, right temporal, left temporal, and occipital areas, as shown in Fig. 1.

2.3. Procedure for analyzing the ACF

A normalized ACF can be expressed by

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)} \qquad (3)$$

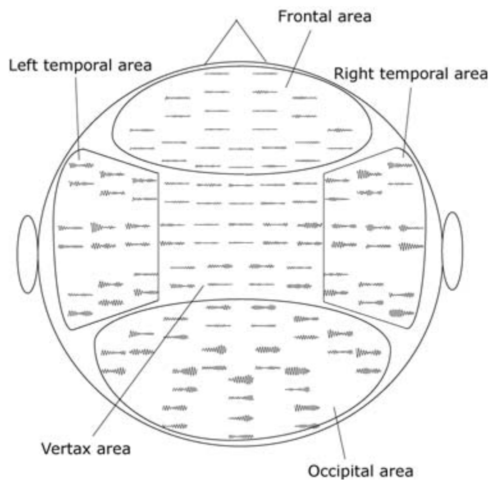

Fig. 1. Example of recorded MEG between 8-13 Hz. Duration of responses is 1.0 s.

where

$$\Phi(\tau) = \frac{1}{2T} \int_0^{2T} \alpha(t)\alpha(t+\tau)dt \tag{4}$$

where 2T is the integral interval, τ is the time delay, and $\alpha(t)$ is the MEG signal. The average power can be determined by either calculating $\Phi(0)$ over time or integrating the power spectral density over frequency. Figure 2(a) shows an example of a measured ACF. Figure 2(b) shows the absolute value of the ACF in logarithmic form as a function of the delay time. To calculate the degree of the ACF envelope-decay, the effective duration, τ_e, is determined. The effective duration of the normalized ACF, τ_e, is defined by the time taken for the ACF envelope to reduce to ten percent of its original value, representing repetitive features within the signal itself. As shown in Fig. 2(b), a straight-line regression of the ACF can be drawn by using only the initial declining portion, 0 dB > 10 log$|\phi(\tau)|$ > -5 dB [4]. In most cases, the envelope decay of the initial part of the ACF may be fitted to a straight line. The values of average power $\Phi(0)$ and τ_e were analyzed at 2T = 1.0 s.

Let the two MEG signals be Δt_1 and Δt_2. The CCF is then defined by

$$\Phi_{12}(\tau) = \frac{1}{2T} \int_{-T}^{+T} \alpha_1(t)\alpha_2(t+\tau)dt. \tag{5}$$

The normalized CCF is given by

$$\phi_{12}(\tau) = \frac{\Phi_{12}(\tau)}{\sqrt{\Phi_{11}(0)\Phi_{22}(0)}}, \tag{6}$$

where $\Phi_{11}(0)$ and $\Phi_{22}(0)$ are the ACFs of $\alpha_1(t)$ and $\alpha_2(t)$ at τ = 0, respectively. The normalized CCF between the MEG responses recorded at the reference channels and those recorded at the test channels were calculated. Examples of a normalized CCF between MEGs between 8-13 Hz are shown in Fig. 3. A positive lag (τ > 0) means that the activity at the reference channel was delayed relative to that at the test channel. $|\phi(\tau)|_{max}$ was defined as the maximum value of the CCFs in the range of τ > 0 as shown in Fig. 3. The values of $|\phi(\tau)|_{max}$ were analyzed at 2T = 1.0 s.

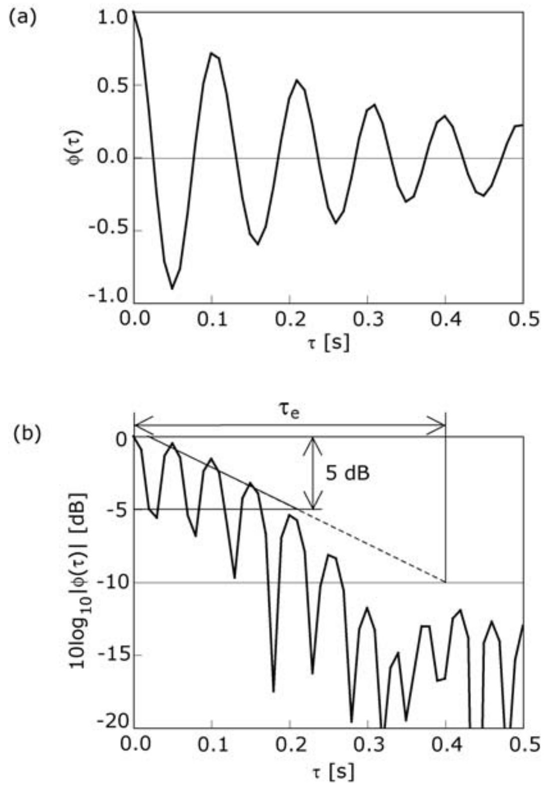

Fig. 2. (a) Examples of normalized ACF of MEG alpha between 8-13 Hz and the definitions of ϕ_1 and τ_1. (b) Examples of determining the effective duration of ACF (τ_e).

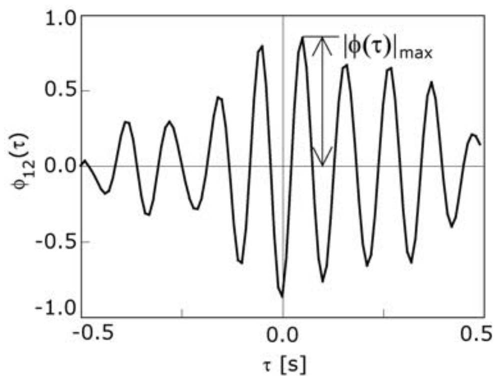

Fig. 3. Examples of normalized CCF of MEG between 8-13 Hz and the definitions of $|\phi(\tau)|_{max}$ and τ_m

3. RESULTS

The averaged τ_e and $\Phi(0)$ values in each frequency band (4-8, 8-13, 13-30, and 30-50 Hz) are shown in Figs. 4(a) and (b). As for τ_e values in the MEG between 30-50 Hz, the initial part of the ACF envelope did not decline monotonically, so that τ_e could not be defined. The averaged $|\phi(\tau)|_{max}$ values of all combinations of reference channels and test channels in each frequency band are shown in Fig. 4(c). Since the values of τ_e, $\Phi(0)$ and $|\phi(\tau)|_{max}$ in the MEG frequency band except between 8-13 Hz did not vary with the change of IACC,

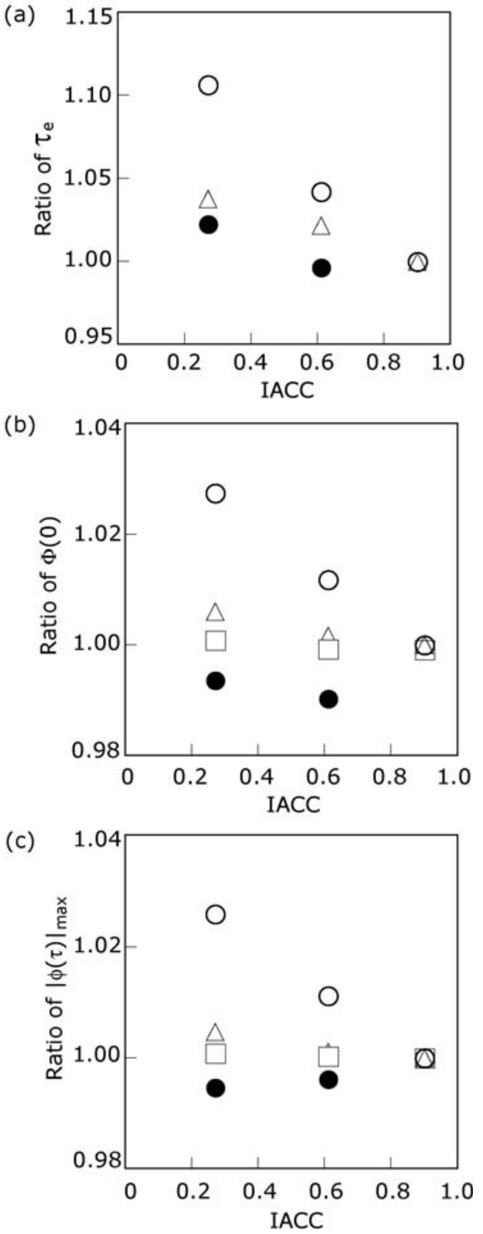

Fig. 4. Averaged (a) τ_e, (b) $\Phi(0)$, and (c) $|\phi(\tau)|_{max}$ values at (○): 4-8 Hz, (●):8-13 Hz, (△):13-30 Hz, and (□): 30-50 Hz. The averaged τ_e and $\Phi(0)$ values in each frequency band were normalized by the τ_e, $\Phi(0)$, and $|\phi(\tau)|_{max}$ values at IACC = 0.90.

further analysis was conducted only at an MEG between 8-13 Hz.

The averaged τ_e and $\Phi(0)$ values of the MEG between 8-13 Hz from five areas are shown in Figs. 5(a) and (b). A two-way analysis of variance (ANOVA) (IACC versus analyzed area) showed a significant effect of IACC and the analyzed area on τ_e ($p < 0.001$) and $\Phi(0)$ ($p < 0.001$). The results indicate that the values of τ_e increased as the IACC decreased, especially in the occipital and temporal areas. The values of τ_e in the occipital area were the longest of the five areas. The

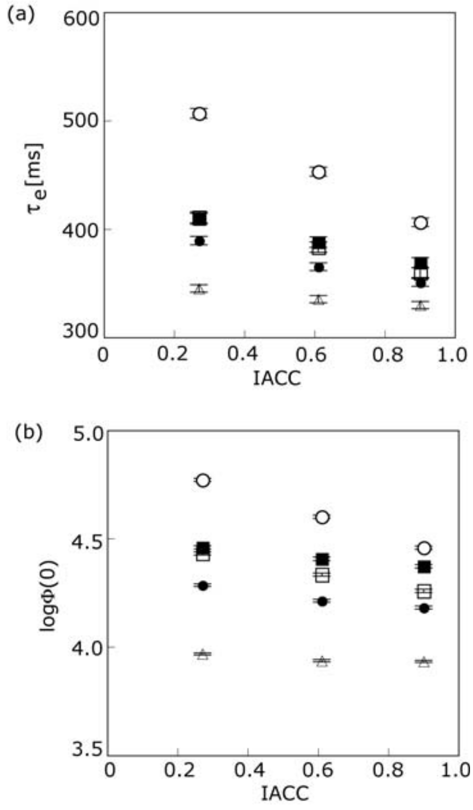

Fig. 5. Averaged (a) τ_e, (b) $\Phi(0)$ values at MEG between 8-13 Hz from (△): frontal, (●):vertex, (□): left temporal, (■): right temporal, (○): occipital areas. Error bars are the 95% confidence interval.

values of $\Phi(0)$ increased as the IACC decreased especially in occipital area.

The averaged $|\phi(\tau)|_{max}$ values of the MEG between 8-13 Hz from five areas are shown in Figs. 6. As shown in Fig. 1, larger MEG responses in the frequency range of 8-13 Hz were found around the temporal and occipital areas. We then focused on the $|\phi(\tau)|_{max}$ values from the reference channels in the temporal and occipital areas. The results from the channel showed maximum $|\phi(\tau)|_{max}$ values in each of three areas; the right temporal, left temporal, and occipital areas, as shown in Figs. 6. A two-way analysis of variance (ANOVA) (IACC versus analyzed area) showed a significant effect of the IACC and the analyzed area on the $|\phi(\tau)|_{max}$ ($p < 0.001$). The results indicate that the values of $|\phi(\tau)|_{max}$ increased as the IACC decreased. $|\phi(\tau)|_{max}$ values were usually large between adjacent channels but decreased with increasing channel distances.

4. DISCUSSION

The τ_e values of the MEG between 8-13 Hz increased with decreasing IACC. Although subjective preference tests for IACC of speech signals were not conducted, previous data indicated a negative correlation between IACC and subjec-

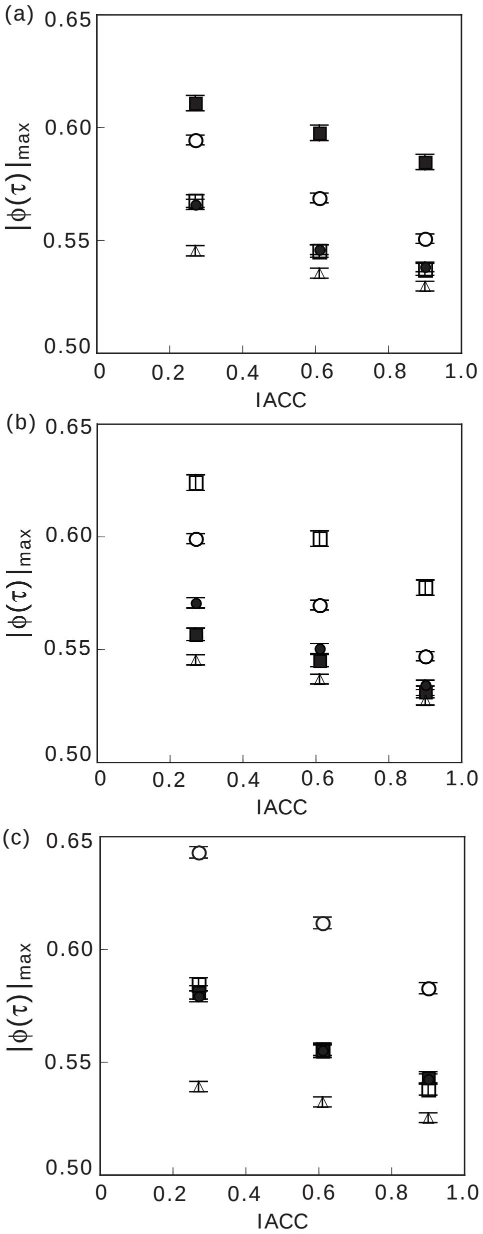

Fig. 6. Averaged $|\phi(\tau)|_{max}$ values at MEG between 8-13 Hz from (△): frontal, (●):vertex, (□): left temporal, (■):right temporal, (○): occipital areas. Each figure indicates the result from a different reference position (a) left temporal, (b) right temporal, and (c) occipital area. Error bars are the 95% confidence interval.

tive preference for sound fields, that is, a lower IACC is preferred [1-3]. The value of τ_e is the degree of similar repetitive features included in the MEG between 8-13 Hz. Therefore this result could mean that the brain repeats similar rhythms and is stable under preferred conditions. This result is consistent with previous EEG and MEG research on subjective preferences for sound fields [4-7]. Similarly, the $|\phi(\tau)|_{max}$ values of MEG between 8-13 Hz increase with decreasing IACC in the temporal and occipital areas. The value of $|\phi(\tau)|_{max}$ signifies the degree of similar repetitive features that appear in the MEG responses recorded at two different channels. This result could mean that the brain repeats similar temporal rhythms over a wider area, under preferred conditions. This result is also consistent with previous MEG research on subjective preferences for sound fields [8].

Alpha activity is commonly defined as fluctuations between 8 and 13 Hz that can be detected on the occipital scalp [11]. Several investigators have assumed alpha activity to be generated in the visual cortex. It has been considered an idling rhythm of the visual cortex, because it is blocked by opening the eyes [12]. Similar oscillatory activity seen over the auditory cortex is called α-rhythm (τ refers to temporal), which reflects spontaneous activity of the auditory cortex [13-16]. Occasionally the rhythm is reduced by sound stimuli, but is not dampened by opening the eyes, thereby being different from the occipital alpha [15]. In previous studies on relationships between brain activities, such as those analyzed by the ACF and CCF, and subjective preferences for sound fields, only the left and right temporal areas, that is over the auditory cortex, have been analyzed [4-8]. However, other areas, such as the vertex, frontal and occipital areas, of the brain were analyzed in this study. The results hint at the idea that the occipital area also involves the processing of subjective preferences for sound fields.

In the occipital area, visual information is mainly processed. MEG has been used to study the retinotopic organization of the occipital visual cortex, in which different parts of the visual field are mapped to different areas [e.g., 17, 18]. With regard to subjective preferences for visual stimulus, it has been shown that the preferred stimulus has a significantly larger value of τ_e and $|\phi(\tau)|_{max}$ of an EEG or MEG between 8-13 Hz recorded than that of the least preferred stimulus in the occipital areas [19-22]. This could indicate that alpha activities observed in the occipital area are related not only to subjective preferences for auditory stimulus but also to those for visual stimulus. The subjects heard the stimulus with their eyes closed in subjective preference test for auditory stimulus [4-8], however, the subjects watched the stimulus with their eyes open in subjective preference test for visual stimulus [19-22]. Although it is said that alpha activity in the occipital areas is damped by opening the eyes, the value of τ_e in the occipital areas is correlated with subjective preferences not only for auditory stimulus but also for visual stimulus. Therefore there is a possibility that the occipital alpha rhythm is concerned with subjective preference regardless of modality, that is, it is not modality-specific.

The left hemisphere is mainly associated with time-sequential identification, and the right one is concerned with spatial identifications [23, 24]. Then it was supposed that the effect of the IACC on MEG between 8-13 Hz was found mainly in right hemisphere in this study. To clarify the left and right hemisphere differences, the τ_e values obtained from left and right temporal areas were compared. Although the significant effect of IACC on τ_e values was found in both left and right temporal areas ($p < 0.001$), the significant effect of analyzed area on τ_e values was not found by a two-way ANOVA (IACC versus left and right temporal areas). That is, the value of τ_e of the MEG between 8-13 Hz became significantly longer as the IACC decreases in both right and left temporal areas. This result may be attributed to the fact that the sound signal used in this study was speech. It is shown that human brain has a strong tendency to process speech sounds in the left and music sounds in the right hemisphere [25-29]. Such differences in the stimulus might influence the results for the value of τ_e. In addition, the previous EEG study has showed that the value of τ_e of the EEG between 8-13 Hz became significantly longer as the IACC decreases not only in right (T4, T6) but also left (T5) temporal areas, though the sound source is music [6].

5. CONCLUSIONS

Human cortical responses corresponding to the IACC of sound fields were investigated. The results show that the effective duration of the ACF, τ_e, and the maximum value of the CCF, $|\phi(\tau)|_{max}$, of MEG between 8-13 Hz become larger as the IACC decrease in both left and right hemisphere when the sound source is speech.

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