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MAGNETOENCEPHALOGRAPHIC RESPONSES CORRESPONDING TO INDIVIDUAL SUBJECTIVE PREFERENCE OF SOUND FIELDS

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To investigate human cortical responses that correspond to subjective preference of sound fields, an attempt is made here to analyze the autocorrelation function (ACF) of magnetoencephalography (MEG) under the condition of varying delay time of single reflections. According to previous studies, it is assumed that a similar repetitive feature of the MEG alpha-waves range (8–13 Hz) is related to subjective preference in terms of the effective duration of the ACF. The source signal was the word "piano" which had a 0·35 s duration. The delay time, Δt_1, was varied at five levels (0, 5, 20, 60, and 100 ms). The scale values of the subjective preference of each subject were obtained by the paired-comparison tests. To compare the results of the MEG measurements with the scale values of the subjective preference, combinations of a reference stimulus ($\Delta t_1 = 0$ ms) and test stimuli ($\Delta t_1 = 0$, 5, 20, 60, and 100 ms) were presented alternately 50 times, and the MEGs were analyzed. It is found that subjective preference for each individual and the effective duration of the ACF of the MEG alpha waves are linearly related.

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1. INTRODUCTION

In the field of architectural acoustics, four orthogonal physical parameters of sound fields have been discovered: (1) listening level (LL), (2) initial delay gap between a direct sound and the first reflection (Δt_1), (3) subsequent reverberation time (T_{sub}), and (4) magnitude of interaural cross-correlation (IACC) [1–3]. Recent efforts to describe the important sound characteristics in terms of the auditory pathways and the brain may produce practical and useful solutions. If enough is known about physiological measures, physical environments, for example, concert halls and opera houses, could be designed according to guidelines derived from the knowledge of brain functions.

As reported by Lindsley [4], when considering the brain's activities in relation to human psychological states, an electroencephalography (EEG) corresponds well to alpha rhythm, which is associated with relaxed states and free creative thought. Alpha activity is commonly defined as fluctuations between 8 and 13 Hz that can be detected on the

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occipital scalp [5]. A similar spontaneous activity exists in the auditory cortex [6–8]. To investigate the relationship between the EEG alpha-brain waves and subjective preferences of a sound field, Ando and Chen [9], Chen and Ando [10] and Nishio and Ando [11] developed a method of using the autocorrelation function (ACF) to analyze brain waves. They analyzed the effective duration of the envelope of the normalized ACF (τ_e) of the alpha waves when the temporal factors Δt_1, T_{sub} and IACC were varied. Their results showed that the τ_e of the alpha waves was significantly longer in the left hemisphere for the preferred conditions of these temporal factors, Δt_1 and T_{sub}. On the other hand, the τ_e of the alpha waves was significantly longer in the right one for the preferred conditions of spatial factor, IACC.

The EEG, which measures electric potential differences on the scalp, is a widely applied method for investigating the functions of the human brain. The magnetic responses produced by electric currents flowing in neurons can be analyzed by magnetoencephalography (MEG). In both methods, the measured signals are generated by the same synchronized neuronal activity in the brain and many interesting properties of the working human brain can be studied [12]. In contrast to scalp EEG, extracranial MEG recordings are considerably less distorted by the tissue surrounding the brain. An EEG measured on the scalp is often badly distorted, due to various inhomogeneities in the head. An MEG, in contrast, is produced by less distorted currents that flow through the relatively homogeneous intracranical space. Therefore, MEG should reflect the subjective preference of a sound field more clearly than EEG. The present purpose is to examine whether or not the subjective preference of a sound field reflects the temporal information in the brain's magnetic responses. The relationship between the scale value of the subjective preference of a sound field and the factors extracted from the ACF of the alpha-wave ranges in the brain's magnetic responses are examined.

Principally, two strategies may be followed in electrophysiological studies of mental processes. The first one uses event-related potentials or fields [13–18]. The second approach deals with the analysis of spontaneous EEG or MEG [19–23]. Numerous studies have reported relationships between spontaneous EEG or MEG and mental processes. The present method follows this second approach by using ACF analyses. Auditory steady state responses to amplitude-modulated sounds have been studied by a number of researchers interested in both the tonotopic organization of human auditory cortex [24, 25] and mechanisms of cortical signal generation [26–28]. Such studies have typically used repetitive stimuli and extensive time-domain averaging to detect brain responses or to localize their sources. This approach provides additional information by elucidating dynamic temporal aspects of neural responses. Some applications of the ACF have indicated its effectiveness for the understanding of EEG and MEG dynamics [9–11, 29–32], and the relationship between subjective preference and the ACF factors of MEG alpha waves is demonstrated here. Thus, it is meaningful to use ACF for MEG analysis.

2. METHOD

2.1. SUBJECTIVE PREFERENCE TEST

The source signal was the word "piano" which had a 0·35 s duration. (Figure 1(a)). Figure 1(b) shows the effective duration of the running ACF, τ_e, at 5 ms intervals of the source signal "piano". The minimum value of the moving τ_e, i.e., $(\tau_e)_{min}$, was about 20 ms. The delay time of the single reflection (Δt_1) was set at five levels (0, 5, 20, 60, and 100 ms). The direct sound and a single reflection were mixed and the amplitude of the reflection was

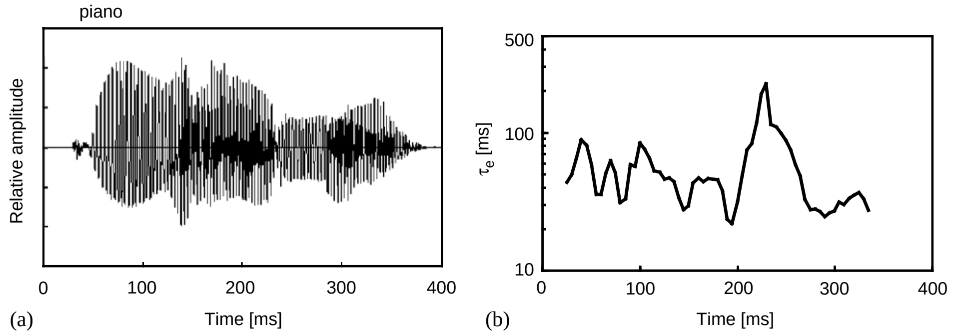

Figure 1. (a) Temporal waveform of sound source "piano". (b) Effective duration of the running ACF, τ_e ($2T = 30$ ms at 5 ms intervals). $[\tau_e]_{min} \approx 20$ ms.

the same as that of the direct sound. The auditory stimuli were binaurally delivered through silicon tubes and earpieces into ear canals. The sound-pressure level, which was measured at the end of the tubes, was fixed at 70 dB (A).

Eight, 23–25-year-old subjects participated in the experiment. All had normal hearing. They were seated in a dark soundproof room with a comfortable thermal environment and heard the sound stimuli. They were asked to close their eyes to fully concentrate on the speech. In accordance with the paired-comparison method, each subject compared 10 pairs per session, and a total of 10 sessions were conducted for each subject. The interval between the stimuli presentations was 1·0 s, and that between comparison pairs was 4·0 s to allow time for the subjects to respond by pushing one of two buttons. The subjects were asked which stimulus they preferred to hear. The paired-comparison method is considered to be the most effective for examining subjective preferences because the subjects are not required to make absolute judgments. The scale values of the subjective preference of each subject were calculated according to Case V of Thurstone's theory [33, 34]. The model of Case V for all data was reconfirmed by a goodness-of-fit test [35]. The result of the goodness-of-fit test for each subject indicated that the model produced values that had a good match with the observed ones.

2.2. MEASUREMENT OF MAGNETIC RESPONSE

Measurements of magnetic responses were performed in a magnetically shielded room using a 122-channel whole-head neuromagnetometer (Neuromag-122^{TM}, Neuromag Ltd., Finland). The paired-auditory stimuli were presented in the same way as in the subjective preference test. During measurements, the subjects sat in a chair with their eyes closed. To compare the results of the MEG measurements with the scale values of the subjective preference, combinations of a reference stimulus ($\Delta t_1 = 0$ ms) and test stimuli ($\Delta t_1 = 0$, 5, 20, 60, and 100 ms) were presented alternately 50 times at constant 1 s interstimulus interval and the MEGs were analyzed. The magnetic data were recorded continuously with a passband of 0·1–30·0 Hz and digitized with a sampling rate of 400 Hz. Figure 2(a) shows an example of recorded MEG alpha waves. Averaged MEG responses corresponding to stimuli were found especially around 100 ms after the stimulus onset, which is an N1m response, in the left and right temporal areas. Eight channels that had a larger amplitude of N1m response in each hemisphere were selected for the ACF analyses. Each epoch, which is the response corresponding to one stimulus, for each subject was analyzed.

2.3. PROCEDURES FOR ANALYZING THE ACF OF MEG

The ACF provides the same information as the power spectral density of a signal. Figure 2(b) and 2(c) show an example of a measured ACF. The ACF can be characterized by four variables [3, 36]. The first is the energy at zero delay, $\Phi(0)$. The average power can be determined by either calculating $\Phi(0)$ over the time or integrating the power spectral density over the frequency. The second is the effective duration of the normalized ACF, τ_e, defined by the time taken for the ACF envelope to reduce to 10% of its original value, representing repetitive features within the signal itself. The third and fourth factors are the

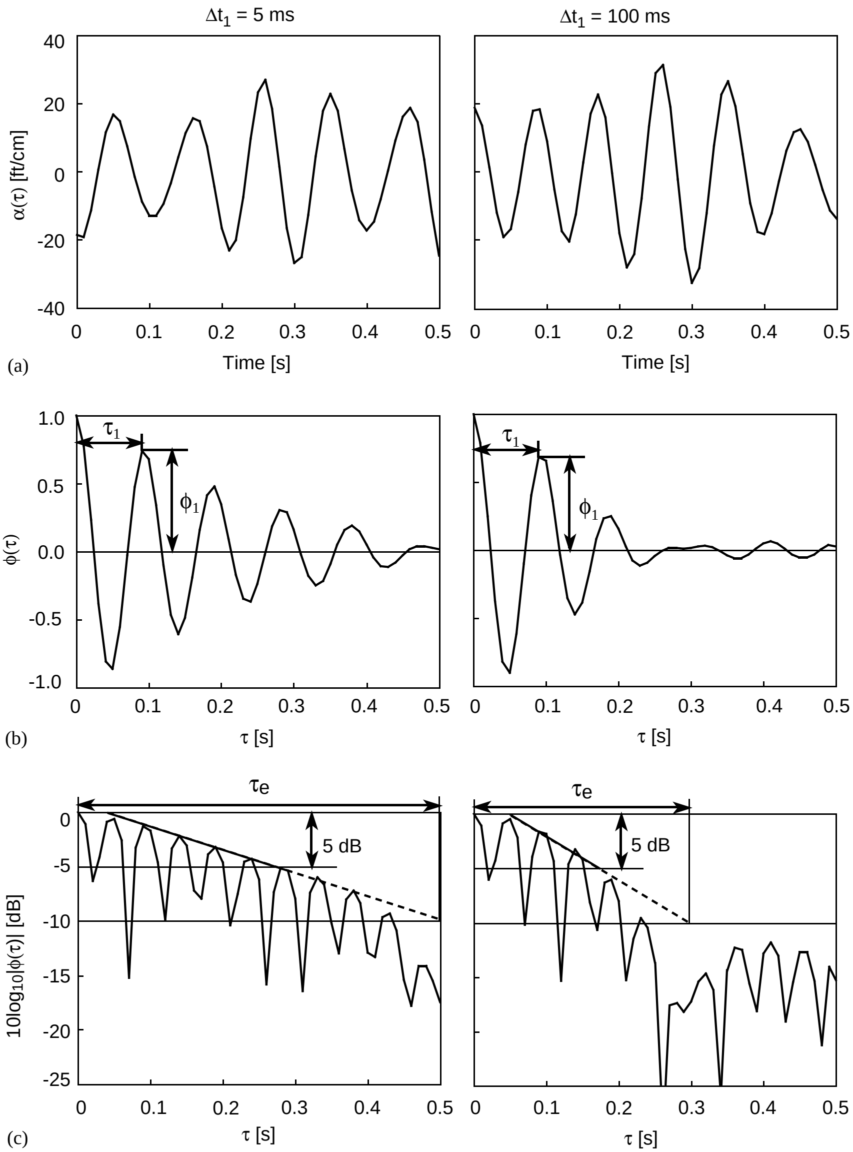

Figure 2. (a) Examples of recorded MEG alpha waves. (b) Examples of normalized ACF of MEG alpha waves and the definitions of ϕ_1 and τ_1. (c) Examples of determining the effective duration of ACF (τ_e). Left, responses to $\Delta t_1 = 5$ ms; right, responses to $\Delta t_1 = 100$ ms.

first peak, ϕ_1, and the delay time, τ_1 (Figure 2(b)). The τ_1 and ϕ_1 values correspond to the fundamental frequency component and its strength. Of course, there are remaining fine structures of a normalized ACF including peaks and dips and their delays; however, there were certain degrees of correlation between τ_n ($n = 1, 2, \ldots$) and ϕ_n. Thus, these parameters can be represented by the last two factors (ϕ_1 and τ_1).

A normalized ACF can be expressed by

$$\phi(\tau) = \Phi(\tau)/\Phi(0), \tag{1}$$

where

$$\Phi(\tau) = \frac{1}{2T}\int_0^{2T} \alpha(t)\alpha(t+\tau)\,\mathrm{d}t, \tag{2}$$

where $2T$ is the integral interval, τ is the time delay, and $\alpha(t)$ is the MEG alpha wave. Figure 2(c) shows the absolute value of the ACF in a 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. As shown in Figure 2(c), a straight-line regression of the ACF can be drawn by using only the initial declining portion, $0\,\mathrm{dB} > 10\log|\phi(\tau)| > -5\,\mathrm{dB}$ [9]. In most cases, the envelope decay of the initial part of the ACF may fit a straight line. The values of τ_e, $\Phi(0)$, and ϕ_1 were analyzed at $2T = 1{\cdot}0$ s. The values of τ_1 were almost the same because of the limited frequency range.

3. RESULTS AND DISCUSSION

A two-way ANOVA (Δt_1 versus left and right hemispheres) showed a significant effect of Δt_1 on the τ_e ($F = 129{\cdot}2$, $p < 0{\cdot}001$), $\Phi(0)$ ($F = 37{\cdot}6$, $p < 0{\cdot}001$), and ϕ_1 ($F = 53{\cdot}5$, $p < 0{\cdot}001$). The correlation coefficients between values of τ_e and $\Phi(0)$ and values of $\Phi(0)$ and ϕ_1 were, respectively, 0·28 and 0·34. However, that between values of τ_e and ϕ_1 was 0·69 ($p < 0{\cdot}001$). The total relationship with eight subjects between the averaged τ_e values and the averaged scale values of subjective preference is linear. Their correlation coefficients were 0·95 ($p < 0{\cdot}01$) in the left hemisphere and 0·92 ($p < 0{\cdot}05$) in the right one (Figure 3(a)). The averaged $\Phi(0)$ values and the scale values of subjective preference showed little relation and their correlation coefficients were 0·33 in the left hemisphere and

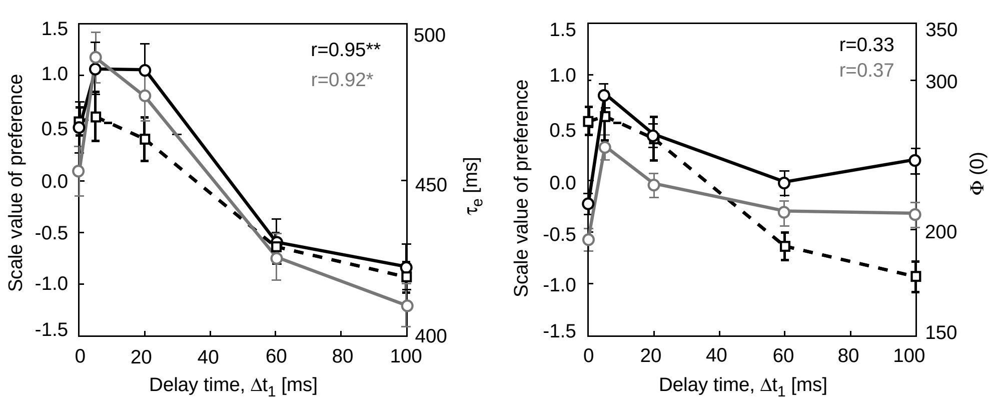

Figure 3. Relationships between scale values of subjective preference and averaged values of (a) τ_e and (b) $\Phi(0)$ over both left and right hemispheres. ......, Scale value of preference; ——, left hemisphere; ——, right hemisphere. Error bars are the 95% confidence interval.

0·37 in the right one (Figure 3(b)). Remarkably, the $\Phi(0)$ values in the left hemisphere were significantly larger than those in the right one ($F = 402{\cdot}0$, $p < 0{\cdot}001$) for all the case of Δt_1. The averaged ϕ_1 values and the scale values of subjective preference showed slightly linear relationships. The correlation coefficients between them were 0·70 in the left hemisphere and 0·74 in the right one. The correlation coefficients between the scale values of preference and the τ_e values are much higher than those between the scale values of preference and the ϕ_1 values. This is consistent with our previous studies on subjective preference for a flickering light [31, 32].

To analyze individual levels, the relationships between the τ_e values and the scale values of individual subjective preference were investigated. As shown in Figure 4, almost direct relationships between the individual scale values of subjective preference and the τ_e values are found. The τ_e is the degree of similar repetitive features included in alpha waves, so that the brain repeats a similar rhythm under the preferred conditions. This tendency for a larger τ_e under the preferred condition is much more significant than the results of previous studies on EEG alpha waves. They studied varying the delay time of a single sound reflection [9, 30], the reverberation time of a music sound field [10], and the tempo of a noise burst [29]. The correlation coefficient between averaged τ_e values and the scale values of subjective preference was 0·80 at most on previous EEG studies. Here, a much clearer relationship between individual subjective preference and the τ_e values was obtained. It is considered that extracranial MEG recordings are considerably less distorted by the tissue surrounding the brain in contrast to scalp EEG.

The left hemisphere is mainly associated with sequential–analytical (verbal–logical) processes, and the right one is concerned with spatial (simultaneous–holistic) processes. For speech signals, the left and right amplitudes of the early slow vertex responses have indicated that the right hemisphere was more activated under the condition of varying the LL and IACC, which are spatial factors of the sound field; whereas the left hemisphere was more activated under the condition of varying the Δt_1, which is a temporal factor of the sound field [1, 13, 37]. The left-hemispheric specialization of speech signals has been investigated by using EEG and MEG [38–40]. Remarkably, the $\Phi(0)$ values in the left hemisphere were significantly larger than those in the right one for all the case of Δt_1 in this study (Figure 3(b)). In addition, the $\Phi(0)$ value in the left hemisphere derived from each subject tended to be larger than that in the right one (Figure 5(a)). Figure 5(b) shows the ratio of maximum to minimum for averaged τ_e values derived from the channel in each hemisphere. The τ_e ratio in the left hemisphere was larger than that in the right one except for a subject ($p < 0{\cdot}05$, Wilcoxon signed-ranks test). This signifies that the range of τ_e in the left hemisphere was wider than that in the right one. Thus, the left hemisphere can dominate changes of the temporal factor Δt_1 of the sound field with speech.

The authors tried to explain the brain magnetic field distributions by using equivalent current dipoles (ECDs). The generator source of N1m was modelled in a spherical head model as the ECDs that in the least-squares sense best reproduced the measured magnetic fields [12]. This was done in each hemisphere by using responses in sets of MEG channels centered at the approximate locations of the left and right auditory cortices. The ECD moments in the left hemisphere were significantly larger than those in the right one ($p < 0{\cdot}05$, Wilcoxon signed-ranks test). It confirms that the left hemisphere dominance for changes of the temporal factor Δt_1 of sound field with speech. However, the ECD moments did not correspond to subjective preference nor Δt_1 as shown in Figure 6. The conventional averaged response was considered only as a rough estimation of the brain's response, and it was claimed that the averaged response does not take into account dynamical changes in the brain's intrinsic activity. On the contrary, single responses were considered as correlates of the brain's quasi-invariant resonant modes containing

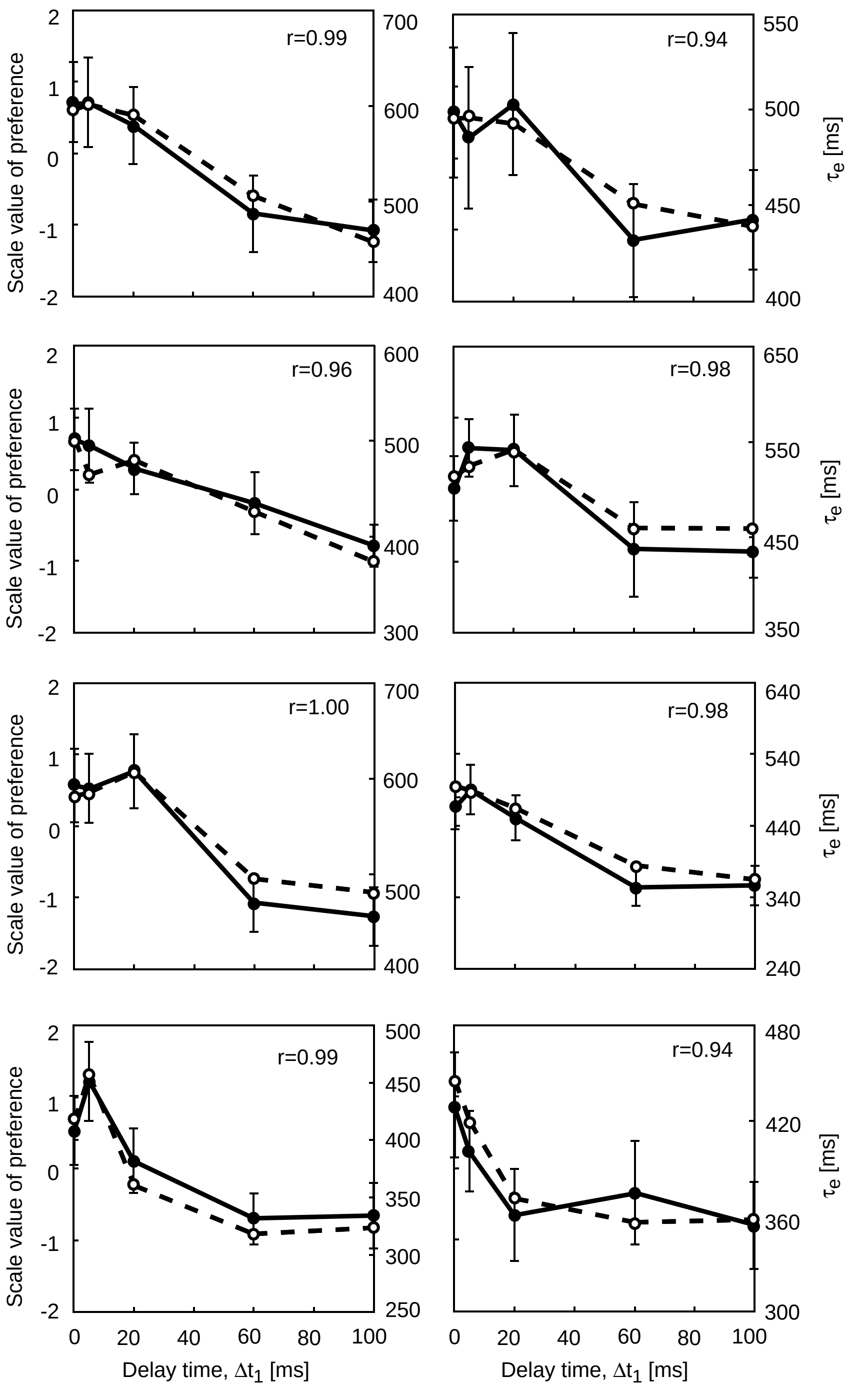

Figure 4. Individual relationships between scale values of subjective preference and averaged τ_e values signify the highest correlations in 16 channels of each subject. ○, scale value of preference; ●, averaged τ_e values. Error bars are standard errors.

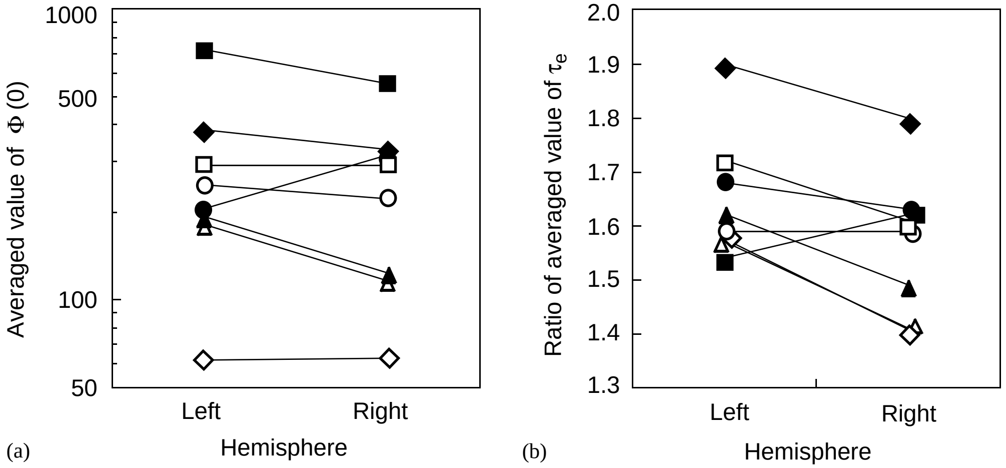

Figure 5. (a) Averaged $\Phi(0)$ values derived from all channels in each hemisphere. (b) Ratio of maximum to minimum for averaged τ_e values derived from each channel in each hemisphere. Each symbol represents one subject.

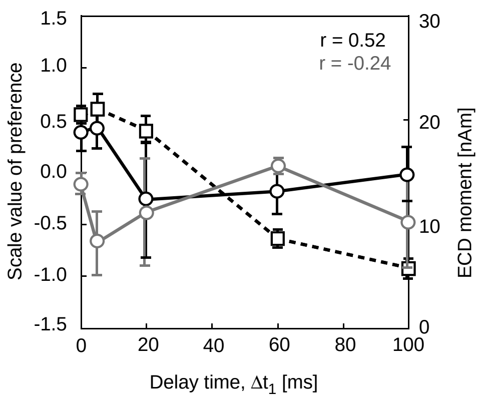

Figure 6. Relationships between scale values of subjective preference and averaged values of the ECD moments over both left and right hemisphere. ...., Scale value of preference; ——, left hemisphere; ——, right hemisphere. Error bars are the standard errors.

important brain codes related to the central nervous system [41]. That is one reason that each epoch, which is the response corresponding to one stimulus, was analyzed by using ACF.

4. CONCLUDING REMARKS

The results of the study lead to the following conclusions:

(1) Subjective preference and the effective duration of the ACF, τ_e, of the MEG alpha wave have a linear relationship.
(2) The energy at zero delay of ACF, $\Phi(0)$ in the left hemisphere is significantly larger than that in the right one ($p < 0{\cdot}001$).

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