Spatial Analysis of Magnetoencephalographic Activities in Relation to Subjective Preference for a Sound Field

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The relationship between human brain response and subjective preference for a sound field was investigated. The source signal was the word "piano", which had a 0.35-s duration. The delay time of reflection in reference to the direct sound, Δt_1, was varied. The scale value of the subjective preference of each subject was obtained by paired-comparison tests. In MEG measurements, combinations of a reference stimulus (Δt_1 = 0 ms) and test stimuli (Δt_1 = 0, 5, 20, 60, and 100 ms) were presented 50 times alternately at a constant 1-s interstimulus interval. The magnetic responses were recorded with a 122-channel whole-head neuromagnetometer and analyzed using a cross-correlation function (CCF). The results showed that the maximum amplitude of the CCF, $|\phi(\tau)|_{max}$, between MEG between 8-13 Hz recorded at two different channels becomes larger during presentations of the preferred condition. The results indicated that the brain repeats a similar temporal rhythm over a wider area under preferred sound fields.

Keywords: cross-correlation function (CCF), magnetoencephalography (MEG), subjective preference

1. INTRODUCTION

Basic knowledge of the temporal activity of the human brain and the relation of this activity to the environment has been obtained from studies using magnetoencephalography (MEG), an noninvasive technique for investigating neuronal activity in human brain [1, 2]. In MEG studies, the weak magnetic fields produced by electric currents flowing in neurons are measured with multichannel SQUID (superconducting quantum interference device) gradiometers; which enable the study of many interesting properties of the working human brain [3]. MEG is closely related to electroencephalography (EEG), which measures electrical potential differences on the scalp. In spite of the different sensitivities of the MEG and EEG methods to sources from different orientations and locations, the primary currents causing the signals are the same. MEG accurately detects superficial tangential currents, whereas EEG is sensitive to both radial and tangential current sources and also reflects activity in the deepest parts of the brain. Only currents that have a component tangential to the surface of a spherically symmetric conductor produce a sufficiently strong magnetic field outside of the brain; radial sources are thus externally silent. Therefore, MEG measures mainly activity from the fissures of the cortex, which often simplifies interpretation of the data. Fortunately, all the primary sensory areas of the brain – auditory, somatosensory, and visual – are located within fissures. The advantages of MEG over EEG result mainly from the fact that the skull and other extracerebral tissues are practically transparent to magnetic fields, but substantially alter current flow. Thus, magnetic patterns outside the head are less distorted than the electrical potentials on the scalp. Further, magnetic recording is reference-free, whereas electric brain maps depend on the location of the reference electrode.

The relationship between spatial brain activity and subjective preference for a sound field was investigated in this study. In the field of architectural acoustics, four orthogonal physical parameters influencing subjective preference for sound fields have been reported: (1) listening level (LL), (2) the 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 interaural cross-correlation (IACC) [4-6]. To investigate the flow of MEG activities over both the left and right hemispheres in relation to subjective preference, cross-correlation function (CCF) analysis was carried out. The temporal frequency band between 8 and 13 Hz was analyzed because this frequency band of EEG and

MEG activities corresponds well to subjective preference [1, 2, 7]. The maximum value of the CCF, $|\phi(\tau)|_{max}$, between MEG measured at different channels was analyzed. It has recently been reported that the temporal factor, which is the effective duration of the autocorrelation function (ACF), τ_e, of MEG between 8-13 Hz, is strongly correlated with subjective preference for a flickering light and Δt_1 of speech [1, 2]. 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. It has also been found that the CCF factor, $|\phi(\tau)|_{max}$, of EEG between 8-13 Hz is correlated with the subjective preference for a flickering light [7]. 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 whether subjective preferences for Δt_1 are reflected in the inter-channel relations between MEG responses in the time domain. The relationship between subjective preferences and the spatial factor, $|\phi(\tau)|_{max}$, extracted from CCF of MEG between 8-13 Hz was examined.

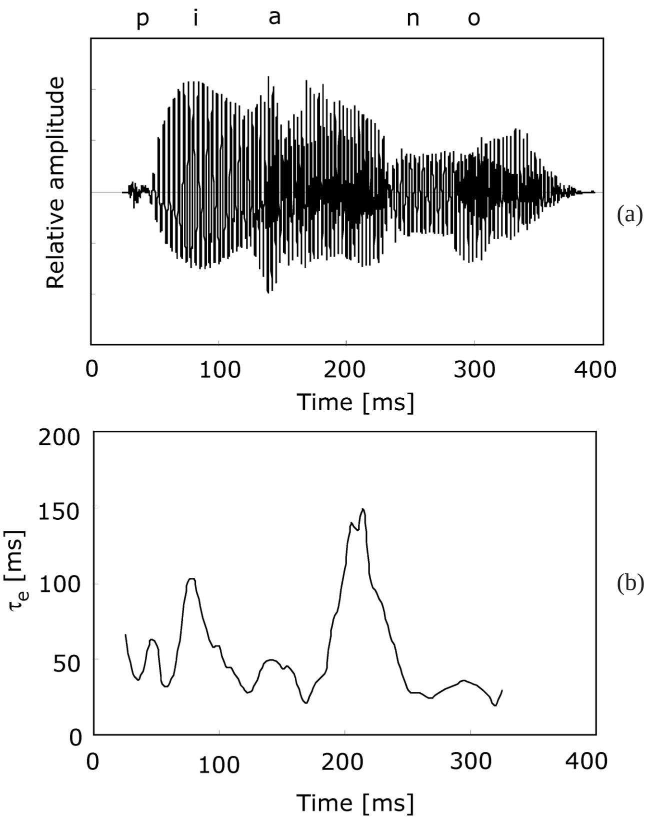

Fig. 1. (a) Temporal waveform of a sound signal, “piano”. (b) Effective duration of the running ACF, $\tau_{e(SS)}$ (2T = 30 ms at 5-ms intervals). $(\tau_{e(SS)})_{min} \approx$ 20ms.

2. METHODS

2.1. Subjective preferences for the delay time of a single reflection in reference to a direct sound

An approximate formula was derived to describe the relationship among the most preferred Δt_1, $[\Delta t_1]_p$, for musical sound fields, the effective duration of the ACF of source signals, $\tau_{e(ss)}$, and the total amplitude A of the pressure amplitude of the reflections A_n [4-6, 8, 9]. It is expressed by

$$[\Delta t_1]_p \approx (1 - \log_{10} A)(\tau_{e(ss)})_{min}, \tag{1}$$

where

$$A = \left(\sum_{n=1}^{\infty} A_n \right)^{1/2}. \tag{2}$$

The amplitudes of reflection relative to that of the direct sound A_1, A_2, ... are determined by the pressure decay due to the paths d_n, such that

$$A_n = \frac{d_0}{d_n}, \tag{3}$$

where d_n is the distance between the source point and the center of the listener’s head. Thus, $[\Delta t_1]_p \approx (\tau_{e(ss)})_{min}$ only when $A_1 = 1$. $[\Delta t_1]_p$ for speech sound fields can be calculated in a same way to that of music by Eq. (1); that is, the $[\Delta t_1]_p$ corresponds well to the $\tau_{e(ss)}$ of the ACF [10, 11]. The speech signal used in this study was a word “piano” in a female voice of 0.35 s duration recorded in an anechoic chamber (Fig. 1a). Fig. 1b shows the effective duration of the running ACF, $\tau_{e(ss)}$, at 5-ms intervals of the source signal. The running ACF can be expressed as a function of time, t, such that [6]:

$$\phi(\tau) = \phi(\tau; t, T) = \frac{\Phi(\tau; t, T)}{\Phi(0; t, T)}, \tag{4}$$

where

$$\Phi(\tau; t, T) = \frac{1}{2T} \int_{t-T}^{t+T} p(s) p(s+\tau) ds; \tag{5}$$

2T is the integral interval, τ is the time delay, and p(s) is a sound signal. The minimum value of the running $\tau_{e(ss)}$, i.e., $(\tau_{e(ss)})_{min}$, was about 20 ms. In this study, the Δt_1 was varied, respectively, to 0, 5, 20, 60, and 100 ms. A direct sound and a single echo were synthesized with the same amplitude. Auditory stimuli were binaurally delivered through silicon tubes and earpieces into ear canals. The total sound pressure was measured with an ear simulator; which included a

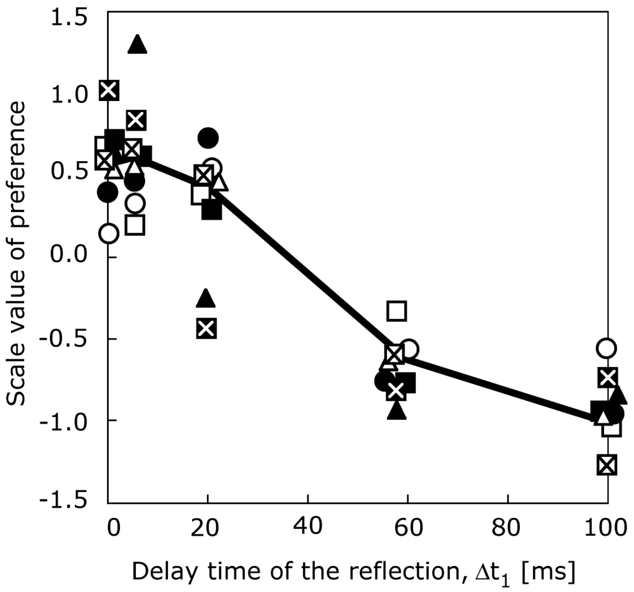

Fig. 2. Scale values of preference as a function of the initial time delay gap, Δt_1.

microphone and a preamplifier, with an adaptor connected to an earpiece. All stimuli had the same sound pressure level (70 dBA) by measurement of the ACF at zero delay, $\Phi(0)$.

Eight 23-to 25-year-old subjects with normal hearing participated in the experiment. Subjects were seated in a dark soundproof room in a comfortable thermal environment and subjected to the sound stimuli. Paired-comparison tests were performed for all combinations of pairs, i.e., 10 pairs (N(N–1)/2, N = 5) of stimuli interchanging the order in each pair per session, and the pairs were presented in random order. A total of ten 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, which allowed time for the subjects to respond by pushing one of two buttons. The scale values of the subjective judgment of each subject, regarded as the linear psychological distance between stimuli, were obtained by applying Thurstone's law of comparative judgment. The scale values of the subjective judgments of each subject were calculated according to Case V of Thurstone's theory [12, 13]. Scale values can be obtained by

$$S_i = \frac{1}{N}\sum_{j=1}^{N} Z_{ij} \qquad i, j = 1, 2, \ldots, N \tag{6}$$

where Z_{ij} is equal to the unit-normal deviate corresponding to the probability P (i > j) that stimulus i is preferred to stimulus j and N is the number of stimuli. The model of Case V for all data was reconfirmed by a goodness of fit test [14]. 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 ($P > 0.1$).

The scale value of preference as a function of Δt_1 is shown in Fig. 2. It is predicted that the preferred delay time, $[\Delta t_1]_p$, is approximately 20 ms [9-11]. The results indicated that the $[\Delta t_1]_p$ from two subjects is 20 ms, but that the $[\Delta t_1]_p$ from other subjects is 0 or 5 ms. In a past study, stimulus was presented

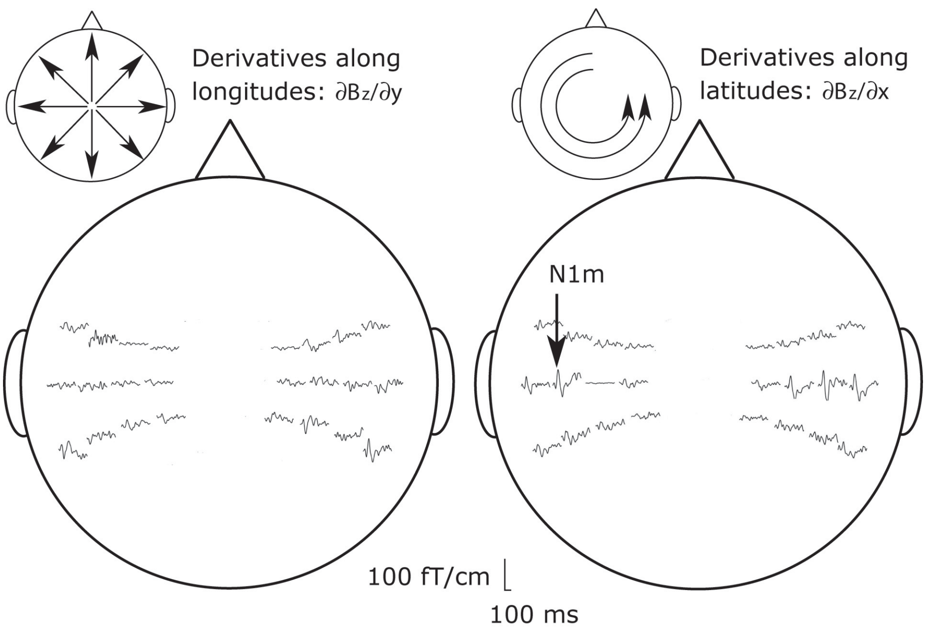

Fig. 3. Example of auditory evoked responses to speech “piano” with 20-ms single reflection; 50 responses were averaged and digitally filtered with a passband of 0.1-50 Hz. The two sets of data show two independent tangential derivatives, B_z, along the longitudes and the latitudes.

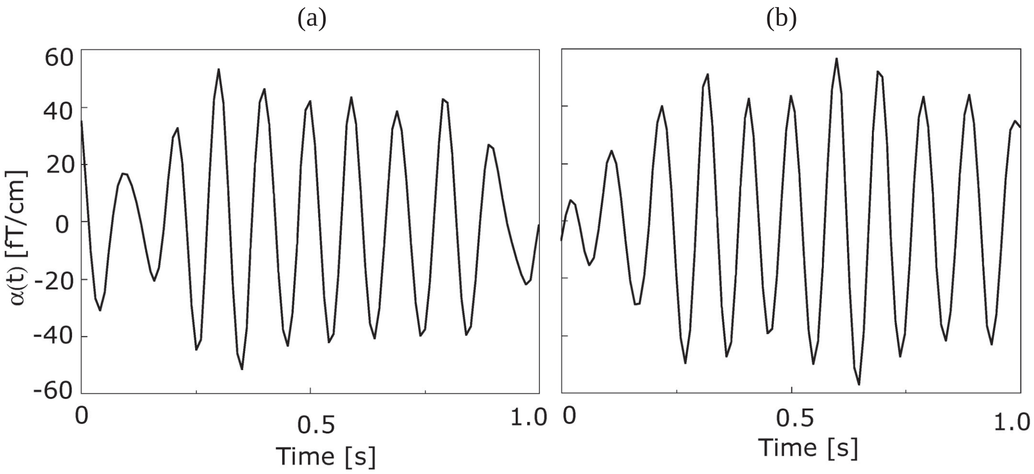

Fig. 4. Examples of recorded MEG between 8-13 Hz.

by two loudspeakers and the simulation of the echo was carried out by using the reflecting transfer function of the echo from a wall [10]. Such differences might influence the results of subjective preference test.

2.2. Recordings of MEG responses

The same subjects used in the preference tests participated in the recordings of the MEG responses, which 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). In this system, the channels are located at 61 sites, and each site has two channels: one measures $\partial B_z/\partial x$ orthogonal tangential derivatives of the magnetic field Bz normal to the surface of the head along the latitude, and the other measures $\partial B_z/\partial y$ along the longitude, as shown in Fig. 3. The paired-auditory stimuli were presented in the same way as in the subjective preference test. During measurements, the subjects sat in a chair and were asked to close their eyes to fully concentrate on the sound. Combinations of a reference stimulus (Δt_1 = 0 ms) and test stimuli (Δt_1 = 0, 5, 20, 60, and 100 ms) were presented alternately 50 times at a constant 1 s interstimulus interval and the MEGs were measured. As shown in Fig. 3, averaged MEG responses corresponding to stimuli were computed, especially around 100 ms after stimulus onset, which is an N1m response, in the left and right temporal areas. Eighteen channels over the auditory cortex, which had a larger amplitude of N1m response than other channels in each hemisphere, were selected for CCF analyses. This resulted in a total of 36 channels being selected for analysis. The recorded data were digitally bandpass filtered with cut-off frequencies of 8 and 13 Hz. Figs. 4(a) and (b) show examples of recorded MEG between 8-13 Hz. Each response, corresponding to one stimulus, was analyzed by CCF for each subject.

2.3. Procedure for analyzing the CCF

Let the two MEG signals in the 8-13 Hz range be $\alpha_1(t)$ and $\alpha_2(t)$, then the CCF is defined by

$$\Phi_{12}(\tau) = \frac{1}{2T}\int_{-T}^{+T} \alpha_1(t)\,\alpha_2(t+\tau)\,dt. \tag{7}$$

The normalized CCF is given by

$$\phi_{12}(\tau) = \frac{\Phi_{12}(\tau)}{\sqrt{\Phi_{11}(0)\,\Phi_{12}(0)}}, \tag{8}$$

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, with 18 channels for each hemisphere, and those recorded at the 35 test channels (the reference channel was excepted) were calculated. The

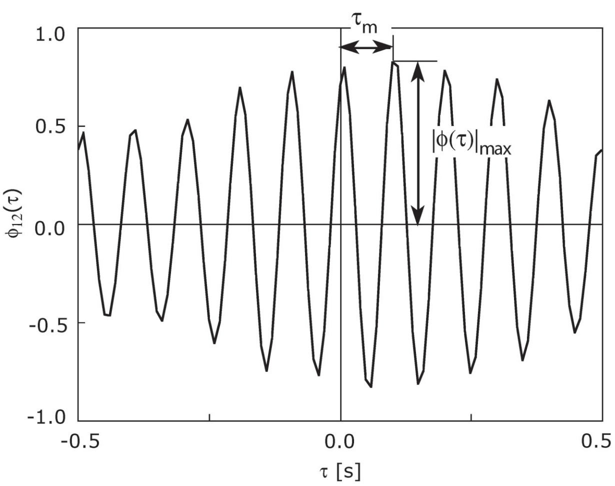

Fig. 5. Examples of normalized CCF of MEG between 8-13 Hz and the definitions of $|\phi(\tau)|_{max}$ and τ_m.

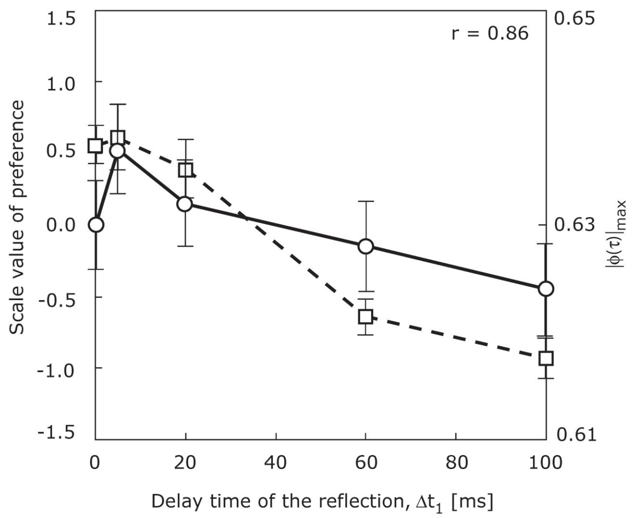

Fig. 6. Relationship between scale values of subjective preference and averaged $|\phi(\tau)|_{max}$ values for all combinations of reference and test channels. □: scale value of preference; ○: averaged $|\phi(\tau)|_{max}$ values. Error bars are standard errors.

integration interval, 2T, for the CCFs was the same (1.0 s) as used in the ACF analysis [1]. Examples of a normalized CCF are shown in Fig. 5. Fig. 5 show the normalized CCF between MEGs between 8-13 Hz measured at the reference channels (Figs. 4(a)) and those measured at the test channels (Figs. 4(b)). A positive lag ($\tau > 0$) 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 $\tau \geq 0$ and τ_m was defined as its delay time as shown in Fig. 5.

3. RESULTS

The relationships between averaged $|\phi(\tau)|_{max}$ values of all combinations of reference channels (36 channels) and test channels (35 channels) and the scale values of subjective preference from eight subjects are shown in Fig. 6. The results indicate that the values of $|\phi(\tau)|_{max}$ increase as the scale values of preference increase. The relationships between the scale values of individual subjective preference and the averaged $|\phi(\tau)|_{max}$ values of all test channels were examined at each reference channel considering individual differences of subjective preference for Δt_1 and head position in the MEG system. The results from the reference channel that signified the highest correlations between the scale values of subjective preference and averaged $|\phi(\tau)|_{max}$ values of 35 test channels in 36 reference channels were then discussed. Though selected reference channels were not always the same among subjects, a relatively larger amplitudes of a N1m response were found in the channel.

Table 1 Results of one-way ANOVA on $|\phi(\tau)|_{max}$ value for each subject

Subject	*F* value	Significance
A	10.54	<0.001
B	7.67	<0.001
C	14.97	<0.001
D	34.61	<0.001
E	23.39	<0.001
F	37.69	<0.001
G	6.34	<0.001
H	21.86	<0.001

Fig. 7 shows examples of the averaged $|\phi(\tau)|_{max}$ values and median values of τ_m as a function of channel distance from two subjects. The $|\phi(\tau)|_{max}$ values were usually large between adjacent channels but, in general, decreased with increasing channel distances. The τ_m values were usually small between adjacent channels but increased with increasing channel distances. These tendencies were more prominent when the channels were derivatives along longitudes, $\partial Bz/\partial x$, because reference channels were also derivatives along longitudes, and the tendencies appeared regardless of preference. In addition, the averaged value of $|\phi(\tau)|_{max}$ for the most preferred Δt_1 was significantly larger than those for the least preferred Δt_1 ($P <$ 0.001).

The results of the $|\phi(\tau)|_{max}$ values were tested by analysis of variance (ANOVA); the results showed that the $|\phi(\tau)|_{max}$ variance was statistically significant in each subject (Table 1). Remarkable findings are shown in Fig. 8, which shows the relationship between averaged $|\phi(\tau)|_{max}$ and scale values of subjective preference for each subject. The results indicate that $|\phi(\tau)|_{max}$ values increase as scale values of preference increase. That is, the preferred Δt_1 has a significantly larger value of $|\phi(\tau)|_{max}$ than that of the least preferred Δt_1.

4. DISCUSSION

The preferred stimulus has a significantly larger $|\phi(\tau)|_{max}$ value between MEG (8-13 Hz) recorded at two different channels than that of the least preferred stimulus. $|\phi(\tau)|_{max}$ signifies the degree of similar repetitive features that appear in MEG responses recorded at two different channels. Significantly larger $|\phi(\tau)|_{max}$ values for MEG between 8-13 Hz indicate that the brain is repeating a similar temporal rhythm over a wider area under the preferred condition, as shown in Fig. 8. When the periods of a flickering light and visual motion are varied,

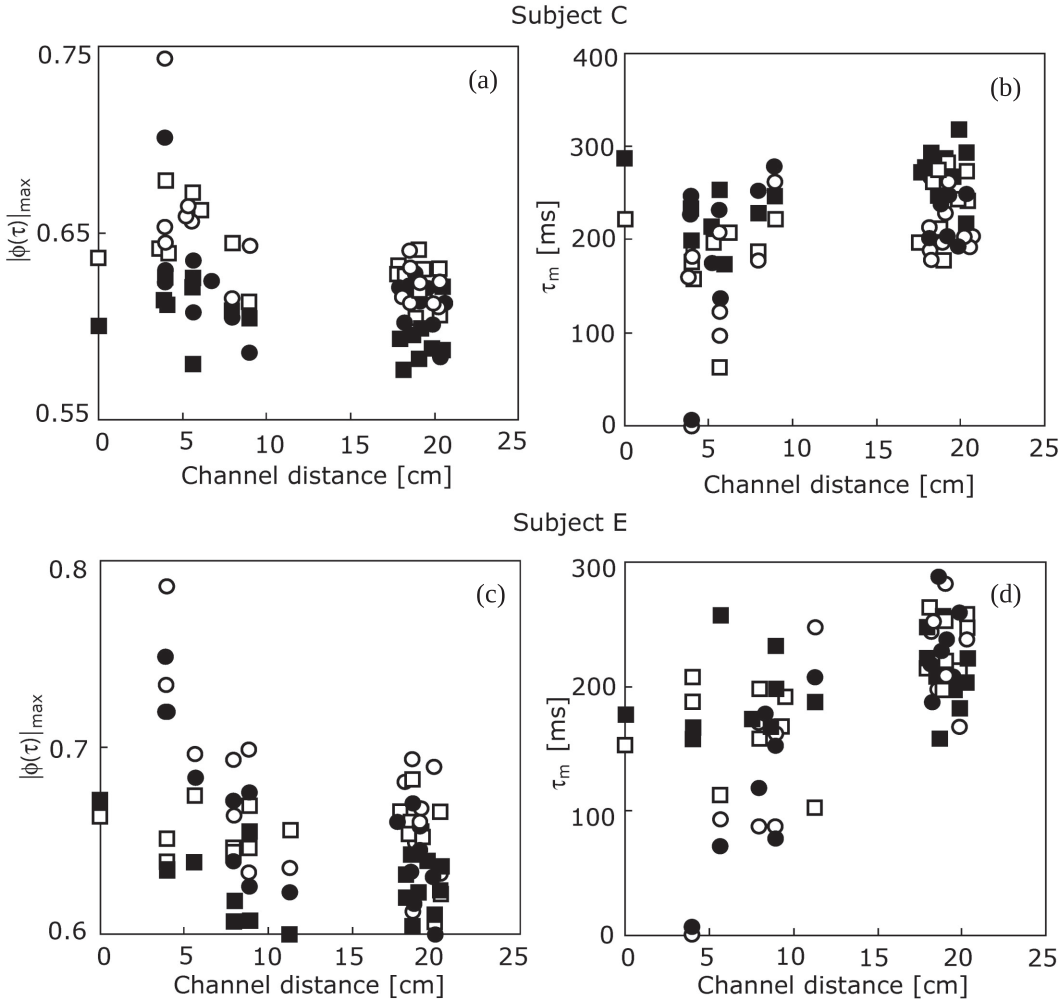

Fig. 7. Examples of the averaged values of $|\phi(\tau)|_{max}$ and median values of τ_m as a function of channel distance. (a) and (c), $|\phi(\tau)|_{max}$; (b) and (d) τ_m. (○): $\partial B_z/\partial x$ to the most preferred Δt_1, (□): $\partial B_z/\partial y$ to the most preferred Δt_1, (●): $\partial B_z/\partial x$ to the least preferred Δt_1, (■): $\partial B_z/\partial y$ to the least preferred Δt_1.

the preferred stimulus has a significantly larger value of $|\phi(\tau)|_{max}$ between EEG between 8-13 Hz recorded at two different electrodes than that of the least preferred stimulus [7, 18], which are consistent with our results.

Alpha activity is commonly defined as fluctuations between 8 and 13 Hz that can be detected on the occipital scalp [15]. Similar oscillatory activity seen over the auditory cortex is called τ-rhythm [16, 17]; and this is what is analyzed by the CCF in this study. The averaged $|\phi(\tau)|_{max}$ values of all combinations of reference channels (36 channels) and test channels (35 channels) in other frequency bands (delta: 1-4 Hz, theta: 4-8 Hz, and beta: 13-30 Hz) are shown in Fig. 9. In delta, theta and beta band, $|\phi(\tau)|_{max}$ values do not increase as scale values of preference increase. If brain waves are somehow correlated to the sound, correlations in delta, theta, and beta bands also will be more pronounced without echo or when the echo delay is short. But it's not the case here. This result clearly confirms that brain is repeating a similar τ-rhythm over a wider area under a preferred delay.

A number of studies have found that the effective duration of ACF, τ_e, of EEG or MEG between 8-13 Hz, a typical temporal factor, is significantly longer for a preferred stimulus than for a non-preferred one [1, 2, 19-23]. The value of τ_e signifies the degree to which the EEG or MEG response between 8-13 Hz exhibits similar repetitive features in the time domain. The significantly longer values of τ_e indicate that the brain is repeating a similar rhythm under these preferred conditions. Thus, under a preferred condition, the brain repeats a similar rhythm over a wider range, in both time and space.

5. CONCLUSIONS

Human cortical responses corresponding to a subjective preference for a sound field were investigated. When the Δt_1 of speech is varied, the preferred stimulus has significantly

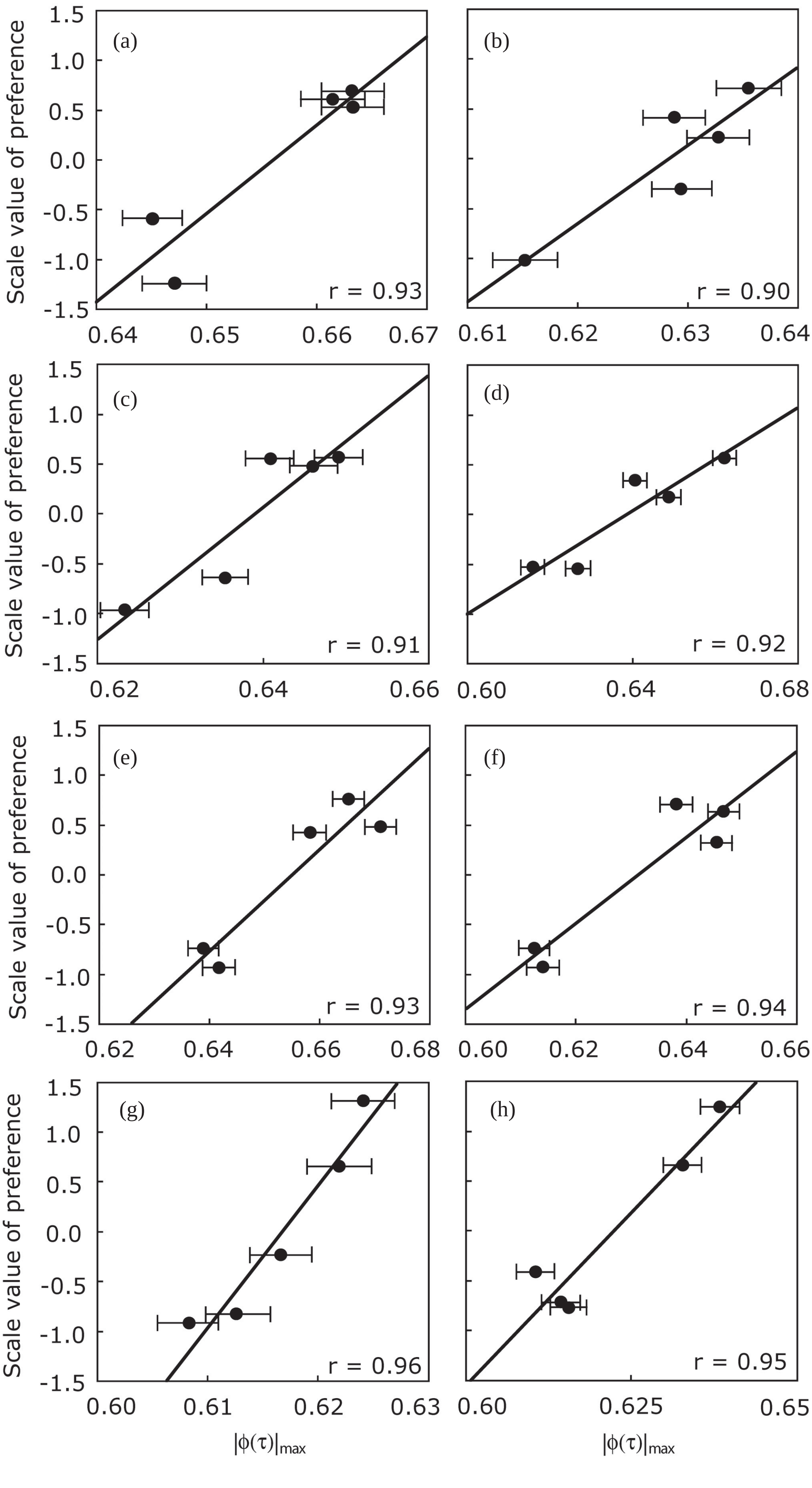

Fig. 8. Relationship between averaged $|\phi(\tau)|_{max}$ values and scale values of subjective preference. Error bars are standard errors. Each figure, (a)-(h), shows the result from a subject. The solid lines represent the results of linear regression analyses between $|\phi(\tau)|_{max}$ values and scale values of subjective preference.

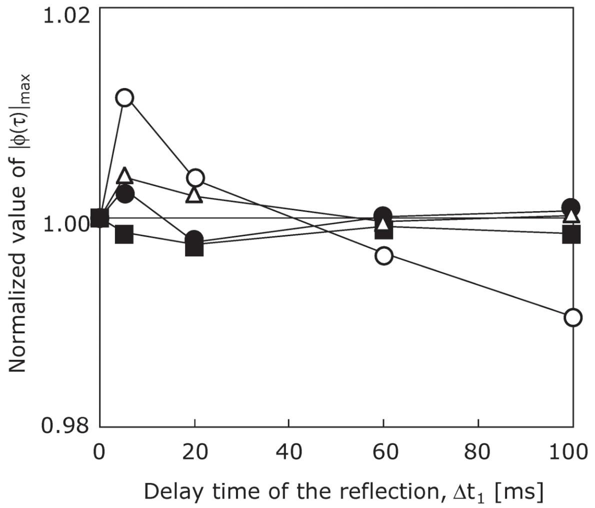

Fig. 9. Averaged $|\phi(\tau)|_{max}$ values for all combinations of reference and test channels at (■): delta, (●): theta, (○): alpha, and (△):beta bands. The averaged $|\phi(\tau)|_{max}$ values in each frequency band were normalized by the $|\phi(\tau)|_{max}$ at Δt_1= 0 ms.

larger $|\phi(\tau)|_{max}$ of MEG between 8-13 Hz than that of the least preferred stimulus. Thus, under the preferred condition, a similar rhythm between 8-13 Hz propagates over a wider area of the brain.

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