Propagation of Alpha Waves Corresponding to Subjective Preference from the Right Hemisphere to the Left with Changes in the IACC of a Sound Field

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(Received 15 January 2003; accepted 6 October 2003)

Attempts are made to clarify the relationship between the person's brain activity and a subjective evaluation of the sound field. For this purpose, we analyzed the autocorrelation function (ACF) of the alpha wave in the electroencephalogram (EEG) measured on the scalp over cerebral hemispheres. The cross-correlation function (CCF) was analyzed to investigate the flow of alpha waves on the scalp over both the left and right hemispheres. To describe the temporal characteristics of the alpha waves, when the magnitude of interaural cross-correlation function (IACC) of a musical stimulus changed, the effective duration of the envelope of the ACF (τ_e) was analyzed. The values of τ_e were found to closely correspond to the subjective preference only in the right hemisphere (electrode T4). For the characteristics of the signal flow on the scalp, the maximum value of the CCF ($|\phi(\tau)|_{max}$) between the alpha waves measured at different electrodes and its delay time (τ_m) were analyzed. The right hemisphere (T4) was found to be activated first, and this activity propagated toward the left hemisphere (T3). The propagation time from T4 to T3 was about 100 ms.

Keywords: electroencephalography (EEG), alpha wave, subjective preference, IACC, autocorrelation function, cross-correlation function

1. INTRODUCTION

The theory of subjective preference enables us to calculate the subjective preference for a sound field through the use of four orthogonal physical factors [1]. These are: the listening level (LL), the initial time-delay gap between the direct sound and the first reflection (Δt_1), the subsequent reverberation time (T_{sub}), and the magnitude of the interaural cross-correlation function (IACC). All of these factors are included in the sound signals arriving at both ears. They have been identified by systematic investigation of sound fields through computer simulation and listening tests (paired-comparison tests) [2]. The subjective preference theory has been validated by tests in actual halls [3-5].

It is quite natural to assume that subjective preference as an overall impression or primitive response of a sound field is reflected in the person's brain activity or physiological responses. This assumption was made in order to investigate the relationship between auditory evoked potential (AEP) and subjective preferences [6, 7]. Slow vertex responses (SVRs) were obtained as AEP from the left and right temporal areas (T3 and T4: according to the International 10-20 System [8]) when each of the acoustical factors was changed. To compare the measured SVRs with subjective preferences obtained by paired-comparison tests, subjects were presented paired stimuli comprising a reference stimulus and a test stimulus. The early-stage amplitude of the SVRs, $A(P_1-N_1)$, showed that hemispheric dominance changed as the acoustic factors were changed. The left hemisphere was dominant when the temporal factor Δt_1 was varied in the paired stimuli [6] and the right hemisphere was dominant when the spatial factors LL or IACC were varied in the paired stimuli [7, 9]. Significantly, N_2-latencies of the SVR from both the left and right hemispheres correspond closely to the subjective preference. The longest latencies were always observed at the most preferred condition.

The above results were obtained by adding the auditory evoked potentials up to 500 ms in the change of the Δt_1, LL and the IACC, using short signals less than 0.9 s. However, for a wide range of the T_{sub}, no useful data could be obtained by the SVR. Alpha waves, which have the longest period of the electroencephalogram (EEG) in the awakening stage, are thought to indicate pleasant and comfortable feelings.

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Therefore, an attempt was made to find a distinctive feature in the alpha wave for the T_{sub} with a long signal duration. To describe the nature of EEG, techniques using the autocorrelation function (ACF) and the cross-correlation function (CCF) have been developed [10, 11]. The ACF can be used to determine temporal characteristics, that is, the degree of persistence of a signal. And the CCF can be used to examine the mutual relationships between two electrode sites, the presence of common components, and transmission time. The spread of alpha waves over the scalp has been studied by using the CCF [12, 13]. The direction of the transverse spread has been reported to be from right to left [14] or to be in no consistent direction [15].

The previous studies cited above except that by [10], examined the nature of EEGs under the condition of no stimulus. To clarify the relationship between the alpha waves and a person's subjective evaluation of the physical environment, we applied the ACF to analyze the effect on alpha waves when the acoustic factors of a musical stimulus changed. A relationship between the change in subjective preference for a sound field with changes in the acoustic factors and the effective duration of the envelope of the normalized ACF (τ_e) of the alpha waves was found [16-18]. The value of τ_e represents a kind of repetitive feature within the signal itself. The values of τ_e of the alpha waves from the left hemisphere (T3) were found to closely correspond to the scale value of the subjective preference when temporal factors Δt_1 and T_{sub} change.

The most effective and widely accepted factor in subjective preference judgment with few individual differences for the sound field is IACC, which is a measure of the difference in the sound signals arriving at both ears [1]. The current study used τ_e of alpha waves to demonstrate right hemisphere dominance when the spatial factor IACC changed. In addition, the flow of alpha waves on the scalp over both the left and right hemispheres was examined by analyzing the CCF between alpha waves measured at different electrodes.

2. METHODS

2.1 IACC of Sound Field

First, let us consider the sound transmission from a sound source in a room to the binaural entrances. Let $p(t)$ be the sound signal as a function of time, t, and let $h_l(t)$ and $h_r(t)$ be impulse responses between the source location and the binaural entrances. Then, the sound signals arriving at the ear entrances are expressed by

$$\begin{aligned} f_l(t) &= p(t) * h_l(t), \\ f_l(t) &= p(t) * h_l(t), \end{aligned} \tag{1}$$

where the asterisk denotes convolution.

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

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_{-T}^{+T} f_l'(t) f_r'(t+\tau)dt, \quad |\tau| \le 1.0 \text{ ms}, \tag{2}$$

where $f_l'(t)$ and $f_r'(t)$ are obtained after passing through the A-weighted network, which approximately correspond to the ear sensitivity, $s(t)$, so that $f_{l,r}'(t) = f_{l,r}(t) * s(t)$.

The normalized interaural cross-correlation is defined by where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the autocorrelation functions at $\tau = 0$ for the left and right ear, respectively.

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}}, \tag{3}$$

The magnitude of the interaural cross-correlation function is defined by

$$IACC = |\phi_{lr}(\tau)|_{max} \tag{4}$$

for the possible maximum interaural time delay, say, $|\tau| \le 1.0$ ms.

Next, consider the test condition with three loudspeakers L_0, L_1, and L_2 fixed at an horizontal angle of $\xi_0 = 0°$ and an elevation angle $\eta = 0°$ (frontal direction), and $\xi_{1,2} = \pm 54°$ ($\eta = 0°$) as shown in Fig. 1. Let $h_{0l}(t)$ and $h_{0r}(t)$, $h_{1l}(t)$ and $h_{1r}(t)$, and $h_{2l}(t)$ and $h_{2r}(t)$ respectively be impulse responses between each loudspeaker and the binaural ear entrances. Then the sound signals arriving at ear entrances are expressed by

$$\begin{aligned} f_l(t) &= p_0'(t)*A_0h_{0l}(t-\Delta t_0) + p_1'(t)*A_1h_{1l}(t-\Delta t_1) \\ &\quad + p_2'(t)*A_2h_{2l}(t-\Delta t_2) \\ &= f_{0l}(t) + f_{1l}(t) + f_{2l}(t) \\ f_r(t) &= p_0'(t)*A_0h_{0r}(t-\Delta t_0) + p_1'(t)*A_1h_{1r}(t-\Delta t_1) \\ &\quad + p_2'(t)*A_2h_{2r}(t-\Delta t_2) \\ &= f_{0r}(t) + f_{1r}(t) + f_{2r}(t) \end{aligned} \tag{5}$$

where $p_0'(t)$, $p_1'(t)$, and $p_2'(t)$ are incoherent signals with each other; A_0, A_1, and A_2 are the pressure amplitudes, A_0 being unity, Δt_0, Δt_1, and Δt_2 are the delay time, and Δt_0 being zero. Under the incoherent condition between the sounds, the normalized interaural cross-correlation function is expressed by

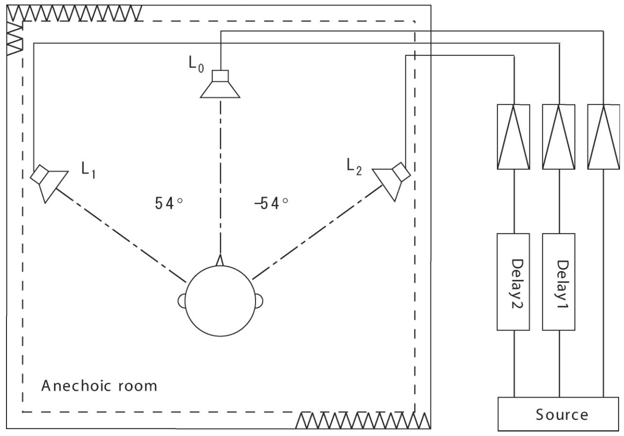

Fig. 1. A diagram of the sound simulation system used in the experiment.

$$\phi_{lr}(\tau)=\frac{\sum_n A_n^2\Phi_{lr}^{(n)}(\tau)}{\sqrt{\sum_n A_n^2\Phi_{ll}^{(n)}(\tau)\sum_n A_n^2\Phi_{rr}^{(n)}(\tau)}},\quad n = 0, 1, 2, \ldots \quad (6)$$

where n denotes the number of sound arriving at the ears, and

$$\Phi_{lr}^{(n)}(\tau)=\frac{1}{2T}\int_{-T}^{+T} f_{nl}(t)f_{nr}(t+\tau)\,dt. \quad (7)$$

Here, $\Phi_{ll}^{(n)}(0)$ and $\Phi_{rr}^{(n)}(0)$ are the autocorrelation functions at $\tau = 0$ for the left and right ear, respectively.

Table 1. Measured correlation functions at $\tau = 0$ for the music motif B as a function of horizontal angle of incidence ξ (elevation angle $\eta = 0°$) [2]

	Horizontal angle ξ a)	
	0°	54°
$\Phi_{lr}(0)$	1.00	–0.28
$\Phi_{ll}(0)$	1.00	0.35
$\Phi_{rr}(0)$	1.00	2.06

a) For $180° < \xi < 360°$, the values may be obtained by setting $\xi = 360° - \xi$ and interchanging the subscripts l and r.

The IACC as a spatial criterion is the significant factor in determining the degree of subjective diffuseness as well as subjective preference for sound field [1]. According to the theory of subjective preference [2], the scale value of a subjective preference in terms of IACC is expressed as

$$S \approx -\alpha(\mathrm{IACC})^{\beta}, \quad (8)$$

where for a number of subjects we obtained $\alpha \approx 1.45$ and $\beta = 3/2$ (Fig. 2). For all subjects tested, the preference increased with decreasing IACC without individual differences, regardless of the source signal used [19, 20]. Small IACC is realized by appropriate reflections from the sidewalls at particular angles according to the spectrum of signals [21].

2.2 Procedure

A music motif (a five-second snippet from the third movement of Arnold’s Opus 48 “Sinfonietta”) was used as the source signal. Two symmetrical lateral reflections with the horizontal angle $\xi = \pm 54°$ added to the frontal direct sound ($\xi = 0°$) were produced in an anechoic chamber (Fig. 1). The distance between the loudspeakers and the center of the subject’s head was 0.90±0.01 m. The loudspeakers were in the horizontal level of the ears of the subject. To produce incoherent conditions, the time delays between the direct sound and the two reflections were fixed at $\Delta t_1 = 20$ ms and $\Delta t_2 = 40$ ms. The IACC values were set to 0.95, 0.65, or 0.30. To obtain these IACC values, the amplitudes of A_1 and A_2 in Eq. (6) were controlled by using the measured values of correlation as a function of the horizontal direction (ξ) for the music motif (Table 1) [2]. Calculated amplitudes for IACC preset at $\tau = 0$ are given in Table 2. The measured normalized interaural cross-correlations, for the integration interval 2T = 2.5 s, are shown in Fig. 3. It is worth noticing that as indicated in Table 2, the measured values of IACC agree well with the calculated values of IACC at $\tau = 0$. The total sound pressure level at the center of the subject’s head was kept constant at a peak of 75 dBA. The maximum values of interaural cross-correlations always occur at $\tau = 0$, which

Table 2. Amplitudes of the reflections ($A_1 = A_2$) relative to that of the direct sound ($A_0 = 0$ dB) calculated by Eq. (6) for preset and measured values of IACC at their amplitudes ($\xi = \pm 54°$, $\eta = 0°$)

Calculated A_1 and A_2 (dB)	Preset IACC (at $\tau = 0$)	Measured IACC (at $\tau = 0$)
–2	1.00	0.95
–7.7	0.65	0.66
–2.7	0.30	0.31

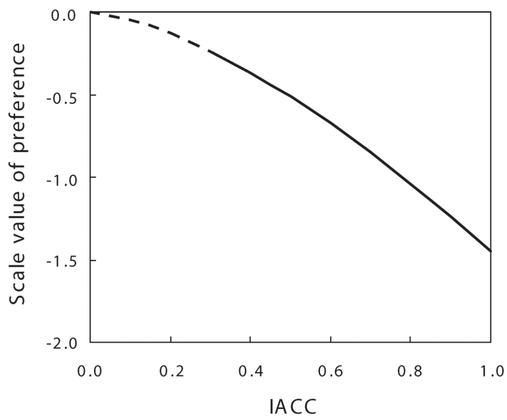

Fig. 2. Scale value of global subjective preference as a function of IACC calculated by Eq. (8) [2].

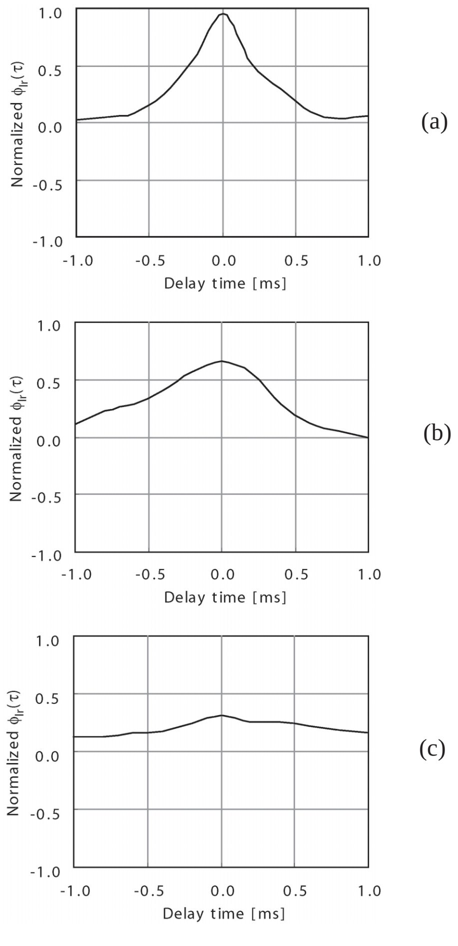

Fig. 3. Measured interaural cross-correlation functions. (a) IACC = 0.95; (b) IACC = 0.65; (c) IACC = 0.30.

verifies the frontal localization of a continuous sound source and thus well-balanced sound field.

2.3 Recording of EEGs

The subjects chosen for the experiment were eight male students with normal hearing ability, all of whom were right-handed. The subjects were asked to abstain from smoking and from drinking of any alcoholic beverage for about 12 hours prior to the start of the experiment.

Each subject was seated in a soundproof chamber with a comfortable thermal environment and asked to close his eyes so as to concentrate fully on the music during the recording of his EEGs. To compare the measured alpha waves of EEG with the scale values of subjective preference which was obtained by paired-comparison, a reference stimulus (IACC = 0.95) was first presented, followed by an adjustable test stimulus (IACC = 0.30 or 0.65). This pair was repeated ten times in each session. The duration of the music signal was 5 s, and the inter stimulus interval was 1 s. The EEG-recording session was repeated three times for each subject, and each session took about two minutes.

The EEGs were measured at positions F7, F8, T3, T4, T5, T6, C3, C4 and Cz. Silver electrodes (7-mm diameter) were affixed to the scalp with electrolytic paste. The reference electrodes were interconnected and placed on the subject's left and right earlobes. When the linked-ear references are used, the reference positions are activated and alpha waves from the electrodes near references indicate low power level. But, as described later, alpha waves were characterized by the parameters extracted from the normalized autocorrelation and cross-correlation function not the amplitude itself. Therefore, the activation of the reference position does not affect these factors. The ground electrode was placed on his forehead. The EEGs were sampled at 100 Hz after passing through a 50-Hz low-pass filter with a slope of 140 dB/Octave. The recorded data were filtered with a digital-bandpass filter with a cut-off frequency of 8-13 Hz (alpha-wave range). To analyze each epoch of the stimulus by ACF and CCF, the sound signal was recorded at the same time.

3. ACF ANALYSIS

3.1 Expression of ACF

The ACF is defined by

$$\Phi(\tau) = \frac{1}{2T}\int_{-T}^{+T} p(t)p(t+\tau)dt. \tag{9}$$

The normalized ACF is given by

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)}\ . \tag{10}$$

In the present study we focus on τ_e of the alpha waves, a significant factor in previous studies [16-18]. We examined the right hemisphere dominance, as was observed in the SVR

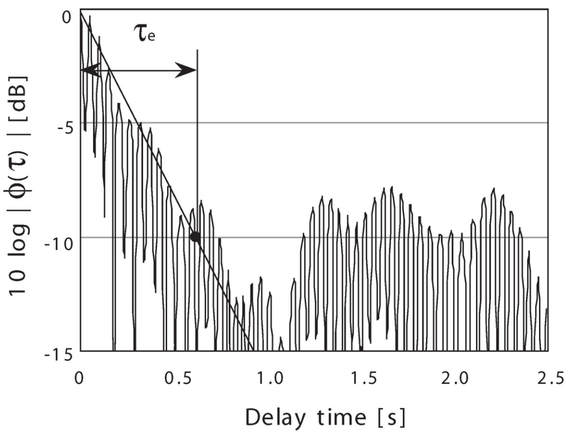

Fig. 4. An example of determining the effective duration of ACF τ_e. The value of τ_e can be obtained from the initial decay rate, extrapolated in the range from the origin to −5 dB.

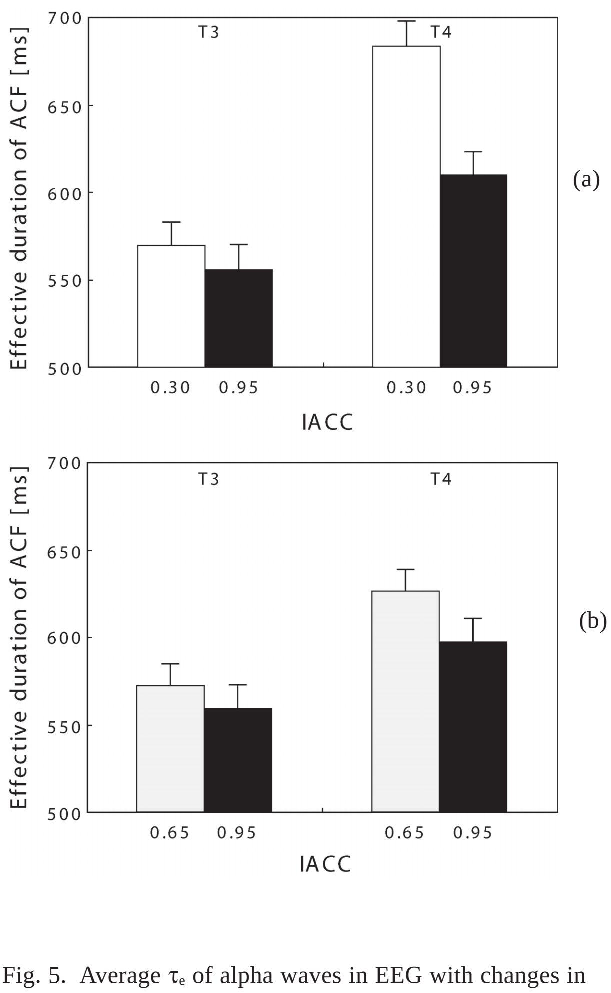

Fig. 5. Average τ_e of alpha waves in EEG with changes in IACC. (a) Pair of sound fields with IACCs of 0.30 and 0.95; (b) Pair of sound fields with IACCs of 0.65 and 0.95. Error bars indicate standard error.

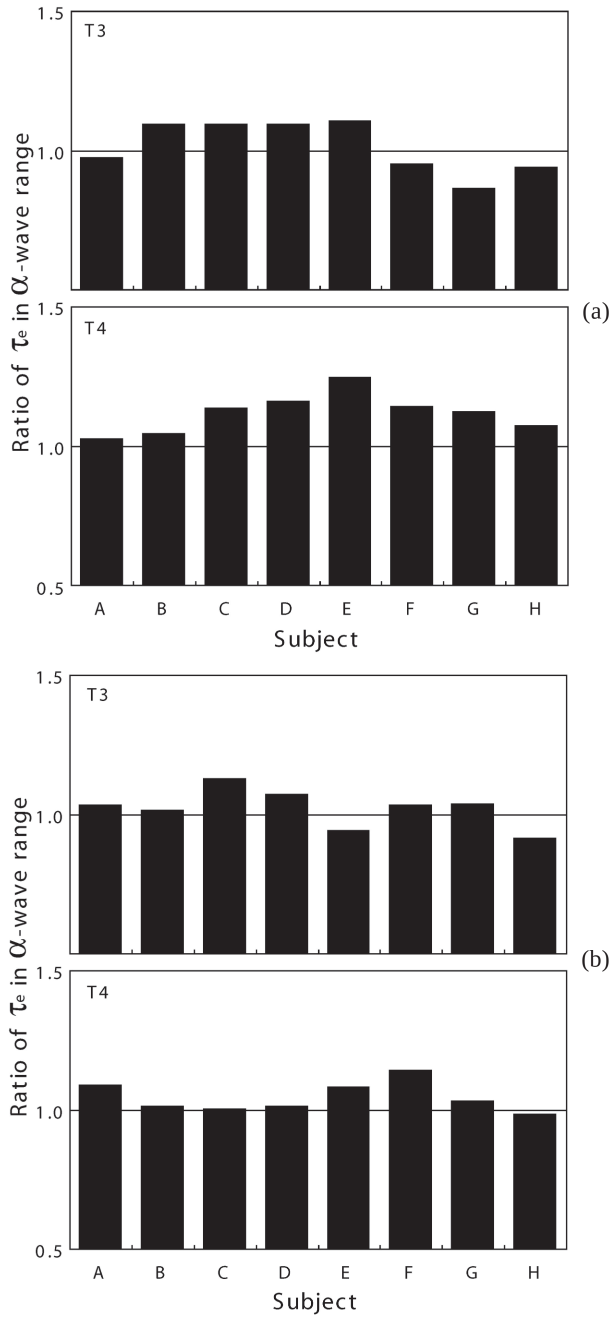

Fig. 6. Ratio of τ_e values of alpha waves in EEG obtained from the T4. (a) [τ_e value at IACC = 0.30]/[τ_e value at IACC = 0.95]; (b) [τ_e value at IACC = 0.65]/[τ_e value at IACC =

analysis, due to the IACC in the ACF analysis. τ_e is defined by the delay at which the envelope of the normalized ACF becomes −10 dB (Fig. 4). In most cases, the envelope decay of the initial part of the ACF can be fitted to a straight line, and τ_e can be obtained from the decay rate extrapolated in the range 0 to −5 dB [16]. The degree of similar repetitive feature of the alpha waves in EEG can be described by the value of τ_e. The integration interval for the ACF was the

Table 3. Results of the analysis of variance for values of τ_e of the ACF of the alpha waves with changes in IACC

Factor	F-ratio	P-Value	F-ratio	P-Value
	Pair of IACCs 0.95 and 0.30		Pair of IACCs 0.95 and 0.65	
Subject	34.41	<0.001	40.47	<0.001
LR	44.87	<0.001	10.18	0.002
IACC	12.74	<0.001	3.45	0.064
Subject*LR	6.52	<0.001	4.08	<0.001
Subject*IACC	1.34	0.230	0.61	0.746
LR*IACC	7.28	0.007	0.15	0.701
Subject*LR*IACC	0.69	0.680	0.59	0.768

Table 4. Comparison of average τ_e of alpha waves in EEG at an IACCs of 0.30 and 0.95. Figures in the parentheses are standered errors

	IACC=0.30	IACC=0.30	
F8	681(17)	668(28)	
T4	684(14)	611(13)	**
T6	752(26)	700(30)	*
C4	635(9)	635(15)	
Cz	646(24)	646(24)	
C3	615(13)	585(17)	
F7	658(26)	672(26)	
T3	571(13)	557(13)	
T5	737(33)	672(30)	*

**: $p < 0.01$; *: $p < 0.05$

same (2T = 2.5 s) as had been used in previous studies [16-18].

3.2 Results

The averaged τ_e of the alpha waves from the left (T3) and right (T4) hemispheres are shown in Fig 5. Clearly, the values of τ_e for the test stimuli with smaller IACCs (0.30 and 0.65) are much longer than those for the reference stimuli with IACC of 0.95 at the T4. A significant difference between the reference stimuli and the test stimuli was observed at the T4 on the right hemisphere when the pair of sound fields with IACCs of 0.95 and 0.30 were presented ($p < 0.001$). The results of the analysis of variance (ANOVA) of the values of τ_e are listed in Table 3. Although there is a large difference among the τ_e of eight subjects ($p < 0.001$), a significant difference is observed for the IACCs in the pair of sound fields with IACCs of 0.95 and 0.30 ($p < 0.001$). The effects of factors "Subject" and "IACC" were independent, because of no interaction in either of the pairs. To discuss the matter in more detail for each subject, the ratio of values of τ_e for the alpha wave are shown in Fig. 6. As shown in Fig. 6(a), all of the subjects had ratios of τ_e ([τ_e value at IACC = 0.30]/[τ_e value at IACC = 0.95]) obtained from the T4 greater than unity. In other words, all the subjects indicate that the values of τ_e obtained from the T4 (right hemisphere) at an IACC of 0.30 were greater than those at an IACC of 0.95. As shown in Fig. 6(b), the ratios of τ_e ([τ_e value at IACC = 0.65]/[τ_e value at IACC = 0.95]) obtained from the T4 were greater than unity expect for subject H. These facts are not true for the other electrodes. The averaged τ_e in the pair of sound fields with IACCs of 0.95 and 0.30 at other electrode positions are listed in Table 4. Significant differences between the reference stimuli and the test stimuli were also observed at the T5 and T6 ($p < 0.05$).

4. CCF ANALYSIS

4.1 Expression of CCF

The CCF is defined by Eq. (2) and the normalized CCF is given by Eq. (3). Since only T4 is significantly activated with changes in the IACC, we calculated the normalized CCF between the alpha waves measured at electrode position T4 and those from the other electrodes (test electrodes) in the pair of sound fields with IACCs of 0.30 and 0.95. The integration interval for the CCF was the same (2T = 2.5 s) as was used in the ACF analysis. An example of a normalized CCF is shown in Fig. 7. Positive lag ($\tau > 0$) means the activity at the test electrode is delayed relative to that at T4. The value of $|\phi(\tau)|_{max}$ was defined as the maximum of the CCFs in the range of $\tau \geq 0$ and τ_m was defined as its delay time, because the $|\phi(\tau)|_{max}$ in the range of $\tau \geq 0$ was significantly

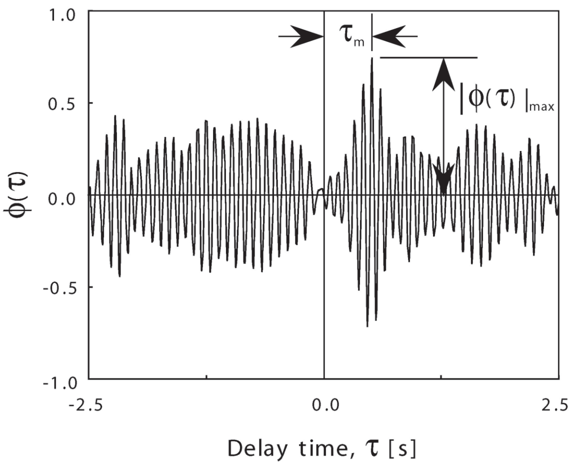

Fig. 7. Definitions of $|\phi(\tau)|_{max}$ and τ_m of normalized CCF between the alpha waves obtained from the T4 and the those from the test electrode.

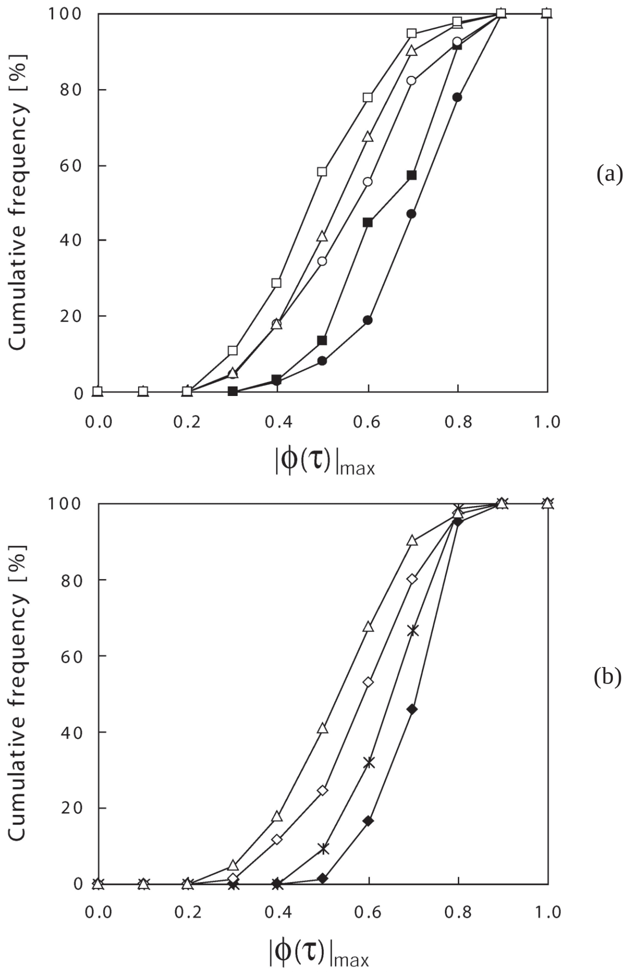

Fig. 8. Cumulative frequency curve of $|\phi(\tau)|_{max}$ at an IACC of 0.30. (a): (●) F8, (■) T6, (○) F7, (△) T3, and (□) T5; and (b) : (◆) C4, (✱) Cz, (◇) C3, and (△) T3.

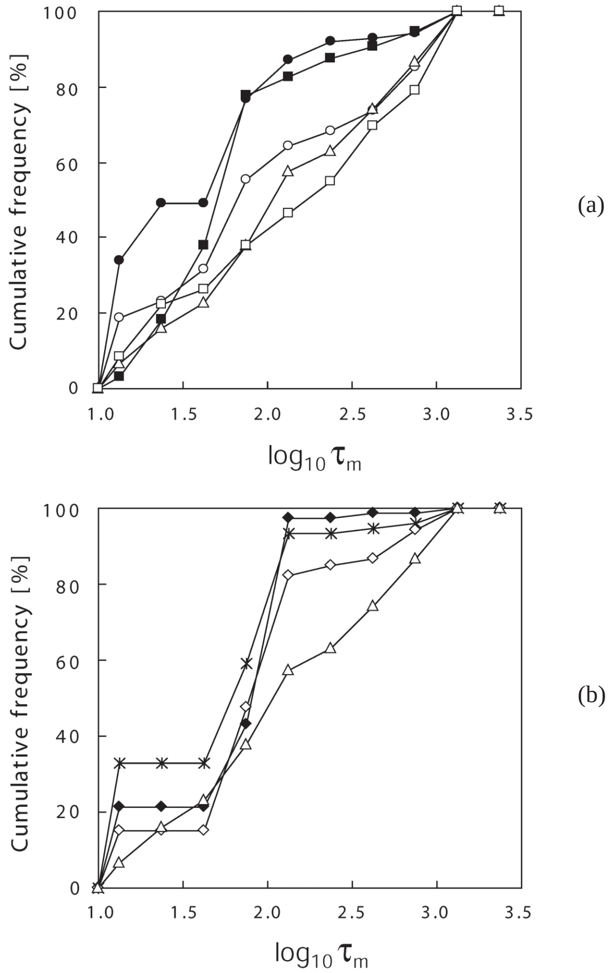

Fig. 9. Cumulative frequency curve of τ_m (logarithmic scale) at an IACC of 0.30. (a) (●) F8, (■) T6, (○) F7, (△) T3, and (□) T5. and (b) : (◆) C4, (✱) Cz, (◇) C3, and (△) T3.

greater than that of $\tau \geq 0$ at an IACC of 0.30 ($p < 0.05$) as listed in Table 5. There was no significant difference between the maximum value of the CCFs in the range of $\tau \geq 0$ and $\tau \leq 0$ at an IACC of 0.95. Thus, we focused on the data at an IACC of 0.30 at which the alpha wave flow from the right to the left hemispheres was observed.

4.2 Results

There is no significant difference between the values of $|\phi(\tau)|_{max}$ at an IACCs of 0.30 and 0.95. Right hemisphere dominance was observed only at an IACC = 0.30 as described in previous section. As shown in Fig. 8(a), the cumulative frequency curves of $|\phi(\tau)|_{max}$ at an IACC of 0.30 for different electrode positions indicates that the median (50%) values of $|\phi(\tau)|_{max}$ in the right hemisphere (F8 and T6) are greater than those in the left hemisphere (F7, T3 and T5). The cumulative frequency curves of $|\phi(\tau)|_{max}$ at an IACC of 0.30 for the electrode positions over the scalp on the corpus

Table 5. Average of maximum value of normalized CCF

(a) IACC=0.30

Test electrode position	Average of $\|\phi(\tau)\|_{max}$	
	$\|\phi(\tau)\|_{max}$ in the range of $\tau \le 0$	$\|\phi(\tau)\|_{max}$ in the range of $\tau \ge 0$
F8	0.757	0.782
T6	0.666	0.734
C4	0.789	0.794
Cz	0.716	0.736
C3	0.668	0.678
F7	0.661	0.661
T3	0.604	0.626
T5	0.529	0.583

(b) IACC=0.95

Test electrode position	Average of $\|\phi(\tau)\|_{max}$	
	$\|\phi(\tau)\|_{max}$ in the range of $\tau \le 0$	$\|\phi(\tau)\|_{max}$ in the range of $\tau \ge 0$
F8	0.751	0.784
T6	0.697	0.709
C4	0.790	0.803
Cz	0.726	0.751
C3	0.710	0.702
F7	0.657	0.646
T3	0.630	0.624
T5	0.596	0.629

callosum (T3, C3, C4 and Cz) are shown in Fig. 8(b). The median value of $|\phi(\tau)|_{max}$ decreases as the distance between the test electrode positions and T4 increases.

Figure 9(a) shows the cumulative frequency curves of $\log_{10}\tau_m$ at an IACC of 0.30 for the electrode positions on the left (F7, T3 and T5) and right (F8 and T6) hemisphere. Figure 9(b) shows the cumulative frequencies of $\log_{10}\tau_m$ at an IACC of 0.30 for the electrode positions over the scalp on the corpus callosum (T3, C3, C4 and Cz). Both results indicate that the median value of $\log_{10}\tau_m$ increases as the distance between T4 and the test electrode positions increases (except for the value at electrode C4). This shows that the alpha waves propagate with the time delay τ_m from T4 to the other electrodes on the corpus callosum. The median value of τ_m indicates that the propagation time of alpha wave from T4 to T3 is about 100 ms. Cross-correlation analysis has been sometimes utilized to investigate the phase difference between the alpha waves from different electrodes. In such cases the time lag between two signals was at most 50 ms [10, 15]. On the other hand, the values of τ_m in this study exceeded 100 ms. The previous studies on the relationship between the CCF of the alpha waves and the subjective preference also had a similar range of τ_m to this study [23, 24]. To obtain the brain activity for the subjective preference, the CCF of the range more than 100 ms should be analyzed.

5. DISCUSSION

Previous studies of paired-comparison tests showed that smaller values of IACC are always preferred regardless of the source signal used (16 subjects in [19]; 106 subjects in [20]). Our results confirm that when the spatial factor IACC is changed, the right hemisphere (T4) is greatly activated andthat the values of τ_e of the alpha waves in this hemisphere correspond to the subjective preference [1]. Only in the right hemisphere, therefore, at the preferred condition of IACC = 0.30, τ_e is significantly longer than that at a IACC of 0.95. In addition, the changes in τ_e of alpha wave in EEG on the left hemisphere with changes in the reverberation time T_{sub} correspond well to the difference in the scale values of the subjective preference of each individual [17].

Measured alpha waves of all subjects in this study indicate that when a preferred test stimulus (IACC = 0.30) is

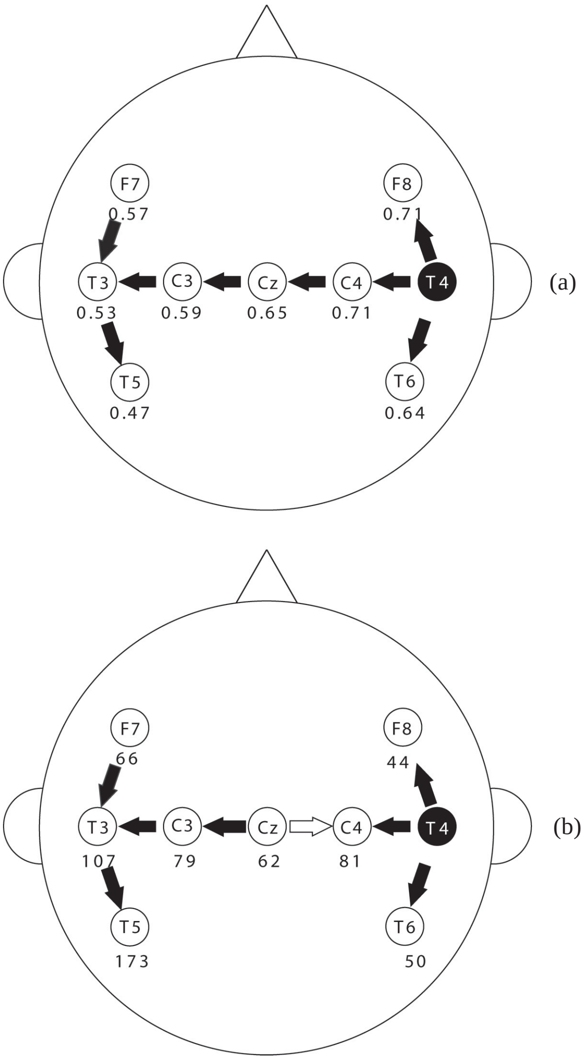

Fig. 10. Alpha-wave flows in both hemispheres with (a) the median (50%) value of $|\phi(\tau)|_{max}$ and (b) the median value of τ_m [ms] at an IACC of 0.30. Black arrow: Flow from the right to the left hemispheres; White arrow: Flow from the left to the right hemispheres.

presented, τ_e in the right hemisphere increases. Since listeners prefer smaller values of IACC without exception, the repetitive feature of the alpha waves apparently signifies the preferred condition of each individual. The τ_e value of alpha wave signifies the degree of similar repetitive features in the time domain. Thus, the longer values of τ_e of the alpha waves were always observed at the preferred conditions.

Right hemisphere dominance was obtained when a musical stimuli was used and the spatial factor was changed in the paired-stimuli. On the other hand, left hemispheric dominance was obtained when the temporal factors were changed with the same musical stimuli and the same method of presentation [16, 17]. Here, the effect of the acoustical parameters not the source signal itself on the alpha wave activity was investigated and the results correspond to the previous ones of hemispheric dominance.

It has been shown that the amplitudes of early SVRs indicate that the left and right hemispheric dominances are respectively due to temporal factor Δt_1 and to spatial factors LL and IACC [6, 7]. The N_2-latencies of the SVR over both hemispheres corresponds well to the scale values of subjective preference [9]. ACF analysis has indicated that τ_e of the alpha waves from dominant hemispheres corresponds to the scale value of subjective preference [16, 17]. Compared with SVR analysis, EEG analysis is advantageous to a signal of longer duration than 0.9 s [17]. Thus, the value of τ_e of the alpha waves is potentially an objective measure for clarifying preferred conditions.

The CCF between the alpha waves clarified the movement of the alpha waves over the scalp from the right (T4) to left hemisphere in change of the IACC. The alpha waves propagate from the right hemisphere (T4) to the left hemisphere with a certain time delay when a test stimulus with an IACC of 0.30 is presented. Such movement is due to callosal connections between the two hemispheres; that is, T4 on the right hemisphere is the initial activity under the preferred condition (IACC = 0.30), and this activity propagates to the other region. The flows of the alpha waves (in relation to the median value of $|\phi(\tau)|_{max}$ and τ_m) at an IACC of 0.30 are shown in Figs. 10(a) and 10(b). The correlation between the values of $|\phi(\tau)|_{max}$ and τ_m is 0.81 ($p < 0.01$). The ACF analyses revealed that the right hemisphere was activated first due to the spatial factors, and then the CCF analysis showed the information flow from the right (T4) to the left hemispheres.

6. CONCLUSIONS

The results of our study lead us to following conclusions:

1. The values of ACF τ_e at an IACC of 0.30 (preferred condition) are significantly longer than those at an IACC of 0.95 (non-preferred condition) only in the right hemisphere (T4) ($p < 0.001$).
2. The values of $|\phi(\tau)|_{max}$ decreases as the distance between T4 and the test electrode positions. Also, the values of τ_m increases as the distance between T4 and the test electrode positions. The median value of τ_m indicates that the propagation time from T4 to T3 is about 100 ms.

ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science.

The authors thank the subjects who participated in the experimental sessions.

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