Auditory Evoked Responses Relating to the Interaural Crosscorrelation of Sound Field

音場에서의 두 귀 상관도와 청각 유발 반응과의 상관

(Seong Hoon Kang*)

강 성 훈*

ABSTRACT

The purpose of this investigation is to examine effects of the interaural crosscorrelation (IACC), relating to subjective diffuseness of sound field, on the auditory evoked response (AER). Using a one-third octave bandpass filtered noise with the center frequency of 500Hz as a source signal, IACC ranging from 0.95 to 0.1 was controlled. AERs to a pair of sounds, i.e., reference sound (IACC=0.95) and test sound(IACC=0.95, 0.75, 0.50, and 0.1), which were presented alternately in order to compare the result with the subjective diffuseness function, were recorded from temporal areas. The information related to the IACC in response to test sounds appeared on latency components, in which a tendency of increasing latency with decreasing the magnitude of IACC was observed. It is noteworthy that the relationship between IACC and latency of AER is found to be linear. These results may be an evidence of the existence of a set of neurons or a mechanism in the auditory brain system which respond to the IACC of sound field.

요 약

본 연구는 음장의 주관 확산감과 관련있는 두 귀에 입사하는 신호의 상호상관도(IACC)와 청각유발 반응(AER)과의 관계를 밝히기 위한 것이다. 실험은 중심 주파수가 500Hz인 1/3옥타브 대역잡음을 이용하여 IACC를 0.95에서 0.1까지 가변시키면서 AER을 기록하였다. IACC와 주관확산감과의 함수 결과와 비교하기 위하여 기준음(IACC=0.95)과 테스트음(IACC=0.95, 0.75, 0.50, 0.1)의 쌍을 교대로 제시하면서 AER을 청각 부위에서 기록하였다. 그 결과 테스트 음에 대한 IACC와 관련된 정보는 AER의 반응시간(Latency)에 나타났고, IACC의 크기가 감소함에 따라 반응시간이 길어지는 경향이 나타났다. 여기에서 IACC와 AER의 반응시간과는 선형관계를 나타냈다. 이 결과는 청각계에서 음장의 IACC에 반응하는 뉴런이나 메카니즘이 존재하는 것을 암시하고 있음을 알수 있다.

I. Introduction

The interaural crosscorrelation (IACC) as a binaural criterion is a significant factor in determining the degree of subjective diffuseness as well as subjective preference to sound field in concert halls[1]-[4]. Subjective diffuseness is mainly determined by strong early reflections arriving from a certain range of azimuth according to the spectrum of signals[5].

The binaural responses related to localization or laterlization in the auditory pathway, based on the auditory brainstem responses with short latency, have been found[6]-[7]. However, the binaural hearing process related to the subjective

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*한국전자통신연구소

diffuseness has not been studied in detail what is the internal processing in the human brain underlying subjective diffuseness perception as a binaural phenomenon? In the subjective diffuseness test, it was found that there is a nonlinear relationship between subjective diffuseness and IACC, in which the scale value of subjective diffuseness is expressed in terms of the 3/2 power of IACC[5].

In order to investigate whether or not there is an activity in the auditory cortex corresponding to the cross-correlation process related to the subjective diffuseness of sound field, auditory evoked response(AER) to different levels of IACC were recorded from temporal areas. The result will be discussed in relation to the subjective diffuseness function.

Ⅱ. METHOD

1. Spatial parameter of sound field

First, let us consider that there is one sound source in a room, and let $h_L(t)$ and $h_R(t)$ respectively be the impulse responses for the paths from the source location to the left and right-ears are written in the following form :

$$f_L(t) = p'(t) * h_L(t),$$

$$f_R(t) = p'(t) * h_R(t), \qquad (1)$$

where $p'(t) = p(t) * s(t)$, $p(t)$ is a sound signal from the loudspeaker, $s(t)$ is the ear sensitivity which is primarily characterized by the external ear and the middle ear[1], and the asterisk denotes convolution.

The interaural crosscorrelation function $\Phi_{LR}(\tau)$ is defined by

$$\Phi_{LR}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} f_L(t) f_R(t+\tau)dt, \ |\tau| \leq 1 \text{ ms} \qquad (2)$$

and the normalized interaural crosscorrelation is given by

$$\Phi_{LR}(\tau) = \Phi_{LR}(\tau) / \{\Phi_{LL}(0)\Phi_{RR}(0)\}^{1/2} \qquad (3)$$

where $\Phi_{LL}(0)$ and $\Phi_{RR}(0)$ are the autocorrelation function of $f_L(t)$ and $f_R(t)$ at $\tau=0$, respectively. The magnitude of the interaural crosscorrelation is defined by

$$\text{IACC} = \max |\Phi_{LR}(\tau)|, \text{ for } |\tau| \leqq \text{ms}. \qquad (4)$$

The delay range of $|\tau| \leqq 1$ ms corresponds to the maximum interaural time difference.

Next, consider the test condition with three loudspeaker L_0, L_1 and L_2 fixed at an azimuth angle and an elevation angle of $\eta=0^0$ (frontal direction), and $\xi_{1,2}=\pm 54^0 (\eta = 0^0)$.

Let $h_{0L}(t)$ and $h_{0R}(t)$, $h_{1L}(t)$ and h_{1R} and $h_{2L}(t)$ and $h_{2R}(t)$ respectively be pressure impulse responses between each loudspeaker and two ear canal entrances. Then, the sound pressures at both ears are expressed by

$$\begin{aligned} f_L(t) &= p_0'(t) * A_0 h_{0L}(t) + p_1'(t) * A_1 h_{1L}(t) \\ &\quad + p_2'(t) * A_2 h_{2L}(t) \\ &= f_{0L}(t) + f_{1L}(t) + f_{2L}(t), \end{aligned} \qquad (5\text{-}1)$$

$$\begin{aligned} f_R(t) &= p_0'(t) * A_0 h_{0R}(t) + p_1'(t) * A_1 h_{1R}(t) \\ &\quad + p_2'(t) * A_2 h_{2R}(t) \\ &= f_{0R}(t) + f_{1R}(t) + f_{2R}(t), \end{aligned} \qquad (5\text{-}2)$$

where $p_0'(t)$, $p_1'(t)$, $p_2'(t)$, are incoherent signals with each other,and A_0, A_1 and A_2 are the pressure amplitudes, A_0 being unity. Under the incoherent condition between the sounds, the normalized interaural crosscorrelation function may be obtained as follows.

$$\begin{aligned} \Phi_{LR}(\tau) = {} & \textstyle\sum_n A_n^2 \Phi_{LR}^{(n)}(\tau) / \\ & \{\textstyle\sum_n A_n^2 \Phi_{LL}^{(n)}(0) \sum_n A_n^2 \Phi_{LL}^{(n)}(0)\}^{1/2}, \\ & n=0, 1, 2, \end{aligned} \qquad (6)$$

where

$$\Phi_{LR}^{(n)}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} f_{nL}(t) f_{nR}(t+\tau)dt.$$

Here, $\Phi_{LL}^{(n)}(0)$ and $\Phi_{RR}^{(n)}(0)$ are the autocorrela-

Table 1. Measured Correlation functions at $\tau=0$ for the 500Hz one-third octave band-passed as a function of horizontal angle of incidence ζ ($\eta=0^\circ$).[1]

	Horizontal angle ζ *										
	0°	18°	36°	54°	72°	90°	108°	126°	144°	162°	180°
$\Phi_{LR}(0)$	1.00	0.84	0.13	−0.54	−1.05	−1.25	−1.10	−0.68	−0.04	0.58	0.94
$\Phi_{LL}(0)$	1.00	0.87	0.87	1.00	1.05	1.11	0.98	0.95	0.78	0.71	0.90
$\Phi_{RR}(0)$	1.00	1.39	1.61	2.36	2.52	2.65	2.59	2.52	1.76	1.29	1.39

*For $180^\circ < \zeta < 360^\circ$, the values may be obtained by setting $\zeta = 360^\circ - \zeta$ and interchanging the subscripts L and R.

Table 2. Relative amplitudes($A_1 = A_2$) calculated by Eq.(6) for preset and measured values of IACC at their amplitudes ($\zeta = \pm 54^\circ$, $\eta = 0^\circ$)

Calculated A_1 and A_2 (dB)	Preset IACC (at $\tau=0$)	Measured IACC (at $\tau=0$)
$-\infty$	1.0	0.95
−11.5	0.75	0.75
−7.3	0.50	0.49
−1.90	0.10	0.11

tion functions of $f_{al}(t)$ and $f_{ar}(t)$ at $\tau=0$, respectively.

In this exprериment, a 500Hz one-third octave bandpass filtered noise was used as the source signal $p_j(t)$ ($j=0, 1, 2$). In order to control the spatial impression of sound field, the magnitude of IACC was adjusted from o.1 to 0.95(IACC=0.1, 0.5, 0.75, and 0.95). According to the subjective diffuseness function[5], these four levels of IACC were selected as equally-spaced scale values.

To obtain a certain IACC value, the amplitudes of A_1 and A_2 by Eq.[6] were calculated using the values given in Table 1(Measured values of correlations as a function of horizontal direction (ζ) for the 500Hz bandpass-filtered noise, where the values only at the origine $\tau=0$ are given [1]). Calaulated amplitudes for IACC preset at $\tau=0$ are given in Table 2.

The measured interaural crosscorrelations (normalized) are shown in Fig.1. It can be seen that the maximum values of interaural cro-

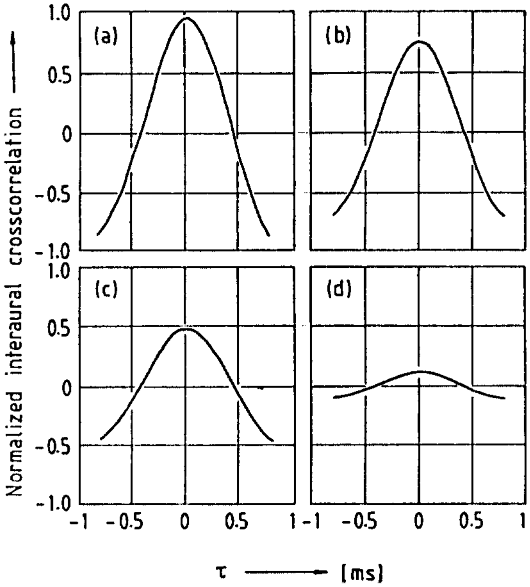

Figure 1. Measured interaural crosscorrelation functions.
(a) IACC=0.95, (b) IACC=0.75
(c) IACC=0.5, (d) IACC=0.1

sscorrelations always occur at $\tau=0$, which verifies the front localization of a continuous sound source.(Note that the maximum value of IACC in a room is usually obtained at $\tau=0$.) As indicated in Table 2, the measured values of ICC agree well with the calculated values of IACC at $\tau=0$.

2. Subjects

The subjects chosen for the experiment were six male and two female students with normal hearing, ranging in age from 18 to 24 years, and their mean age was 21. All the subjects were right-handed as determined by a questionnaire on dominant hand[8], and regarded themselves as right-handed also. Prior to the experiment, the subjects were asked to abstain from smoking and drinking of any kind of alcoholic beverage for about 12 hours[9].

3. Procedure

Each student was comfortably seated in a chair in front of loudspeaders in a sound proof chamber and was told to keep both eyes closed, paying attention to the sound during the experiment.

In order to compare the results with the subjective diffuseness function obtained by paired comparison tests[5], a reference stimulus (IACC=0.95) was presented. Such a pair of stimuli (reference and test stimuli) was presented alternately 50 times ; thus order of stimulus itself had no importance. The duration of each stimulus was 400 ms to avoid off-effect in AER recording, and the interstimulus interval was 600 ms. The rising speed of stimulus was 17 dB/ms, and was held constant across IACC conditions. The sound pressure level was held constant across IACC conditions, and was 70 dBA (slow) at the peak level.

The subjects were not asked to judge any difference in subjective impression between two different sound fields during AER recordings. For each subject, the session was repeated two times within one week and the AERs for the two tests were averaged.

4. Recording evoked responses

The electrical responses were obtained from the left and right temporal areas (T_3 and T_4) according to the International 10-20 System[10]. Silver electrodes (7-mm diameter) with electrolytic paste were used. The reference electrodes were interconnected and located on the left and right ear-lobes. The ground electrode was placed on the forehead.

The evoked electrical signals were amplified using a polygraph (Nihon Kohden, Type EEG 7109) with a bandwidth of 0.3 to 60Hz. Amplified signals were then averaged on-line with a signal averager(Nihon Kohden, Type ATAC-450). The data were sampled at 2 ms intervals and the sweep interval was 512 ms after the onset of stimulus. The evoked responses from both hemispheres were averaged simultaneously. The evoked responses for the two conditions(i.e., reference stimulus and test stimulus) were averaged separately. Amplitude calibration was made by impressing a 50 μV calibration signal on the EEG amplifier.

In averaging AERs, a smoothing metod was used so that the peaks of AER may be clearly definded. The smoothing process is an approximation of low-pass filtering, as described blow. The AER signal can be represented by an X vector of N elements with components X_i ($i=1, 2, \cdots, N$, N being the number of samples). Results of smoothing yield an A vector of N elements such that the i th component is

$$a_i = \frac{1}{p} \sum_{j=-L}^{+L} X_{i+j} \qquad (8)$$

where $i=1, 2, \cdots, N$, and $P=2L+1$ is the number of averaged points. In this study, the number of averaged points P is 9, which corresponds to low-pass filtering with a cut-off frequency of 25Hz. The AERs obtained by smoothing were plotted on an X-Y plotter.

Ⅲ. RESULTS

After each test, all the subjects reported that they were able to discriminate the difference between two sound fields with different levels of LACC.

Eight scores, consisting of three peak-to-peak amplitudes and five latencies, were used as measures of the change of AER due to stimulus. For the response to the test sound, the amplitude difference berween P_1 and N_1 was defined by $A(P_1\text{-}N_1)$, N_1 and P_2 by $A(N_1\text{-}P_2)$, and P_2 and N_2 by $A(P_2\text{-}N_2)$, and amplitude differences were defined by $A(P'_1\text{-}N'_2)$, $A(N'_1\text{-}P'_2)$, and $A(P'_2\text{-}N'_2)$ for the response to the reference sound. The latencies in response to the test sound were the time interval between the onset of stimulus and P_1, N_1, P_2, N_2, and P_3 peaks, and latencies in responce to the reference sound were defined by P'_1, N'_1, P'_2, N'_2, and P'_3.

Fig. 2 is an example of AERs recorded from one subject. Occasionally, a double peak with small amplitude was observed as shown in the upper left part of Fig. 2(IACC=0.95, right hemisphere). However, it can be clearly seen that the latency at N_2 peak in both hemispheres becomes longer as the IACC decreases.

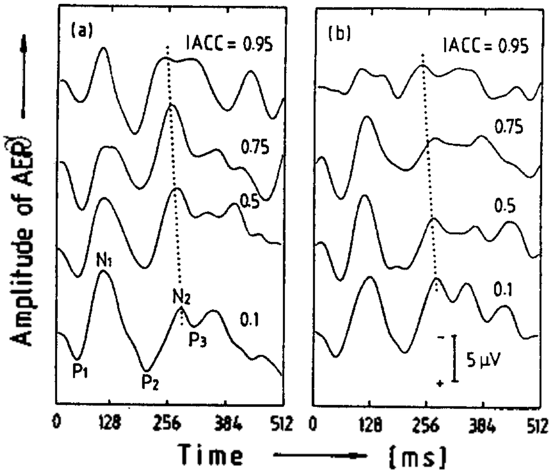

Figure 2. Averaged evoked responses for a single subjest. Dotted lines are the loci of N_2 latency againt IACC. The latency increases as the value of IACC decreases. (a) Left hemisphere, (b) Righr hemisphere. The upward direction indicates negativity.

Fig. 3 shows the mean amplitudes of AERs over the eight subjects for both the test sound field with adjustable IACC and the reference sound field with IACC=0.95, respecitively. Analysis of variance indicated that the first two amplitudes of AER were significantly greater for the right hemisphere than for the left hemisphere [$A(P_1\text{-}N_1)$ ($p<0.05$), $A(N_1\text{-}P_2)$ ($p<0.05$), $A(N'_1\text{-}P'_2)$ ($p<0.05$) $A(N'_1\text{-}P'_2)$ ($p<0.01$)]. $A(N'_1\text{-}P'_2)$ ($p<0.01$)]. On the contrary, the amplitude for the left hemisphere was greater than that for the right in the next amplitude : $A(P_2\text{-}N_2)$ ($p<0.01$), $A(P'_2\text{-}N'_2)$ ($p<0.01$). The effect of IACC was significant for $A(P_1\text{-}N_1)$ ($p<0.01$), $A(N_1\text{-}P_2)$ ($p<0.01$) $A(P_2\text{-}N_2)$ ($p<0.05$), and $A(P'_1\text{-}N'_1)$ ($p<0.05$) but not for $A(N'_1\text{-}P'_2)$ and $A(P'_2\text{-}N'_2)$. As usual, there was variation among the subjects in all cases ($p<0.05$).

Fig. 4(a) shows the mean latencies of each peak from the left and right hemispheres for the eight subjects as a function of IACC of the test sound field. No systematic difference due to IACC was observed for the first three praks P_1, N_1, and P_2. However, changes in latency of the two following peaks N_2 and P_3 over both hemispheres due to IACC were remarkable($p<0.01$) ; the latencies decrease as the magnitude of IACC increases. But, no hemispheric difference was observed in these peaks. As shown in Fig. 4(a) and P_3 shift in parallel according to the magnitude of IACC, implying that the shift of latency with varying IACC begins with N_2 peaks.

The mean latencies of the five peaks in the reference sound field with IACC=0.95 as a function of IACC of the paired test sound field are shown in Fig. 4(b). The latencies in the reference sound field remain nearly constant irrespective of the IACC change of the paired test sound field at all the five latencies.

In order to show individual change due to

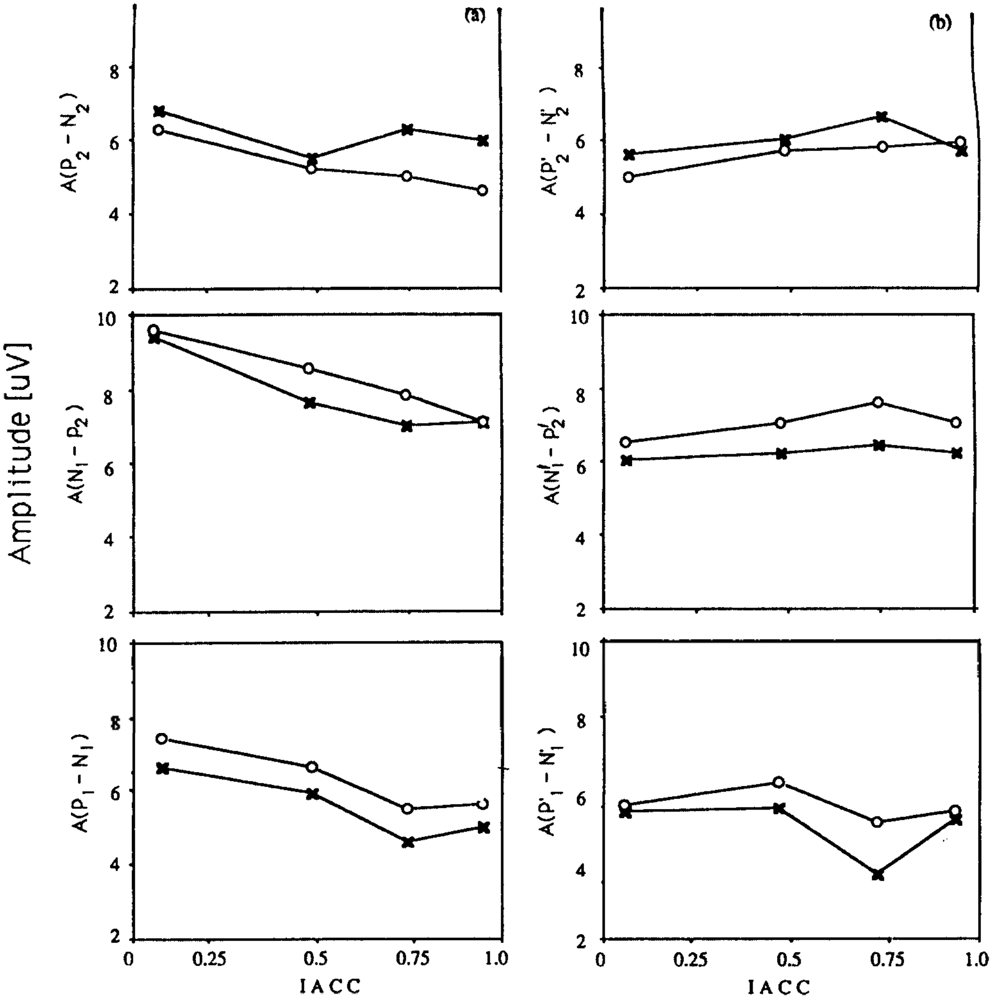

Figure 3. Aveaged amplitudes of AERs over the left and right hemispheres (8 subjects).
× : Left hemispere, ○ : Right hemisphere
(a) Amplitudes as a function of IACC of the test sound field
(b) Amplitudes for the reference sound field with IACC=0.95(as a function of IACC of the paired test sound field).

IACC in response to the test sound, N_2 latency is plotted for the eight subjects as a function of LACC, as shown in Fig.5 . Clearly, for all the subjects latency tends to decrease as IACC increases, except only for the left hemisphere of one subject [indicated by + symbol in Fig. 5(a)].

The relationship between the IACC and the mean latency of N_2 for all the subjects is plotted in Fig. 6. The relationship is found to be remarkably linear, and the correlation coefficient between them is −0.99(1% significance level).

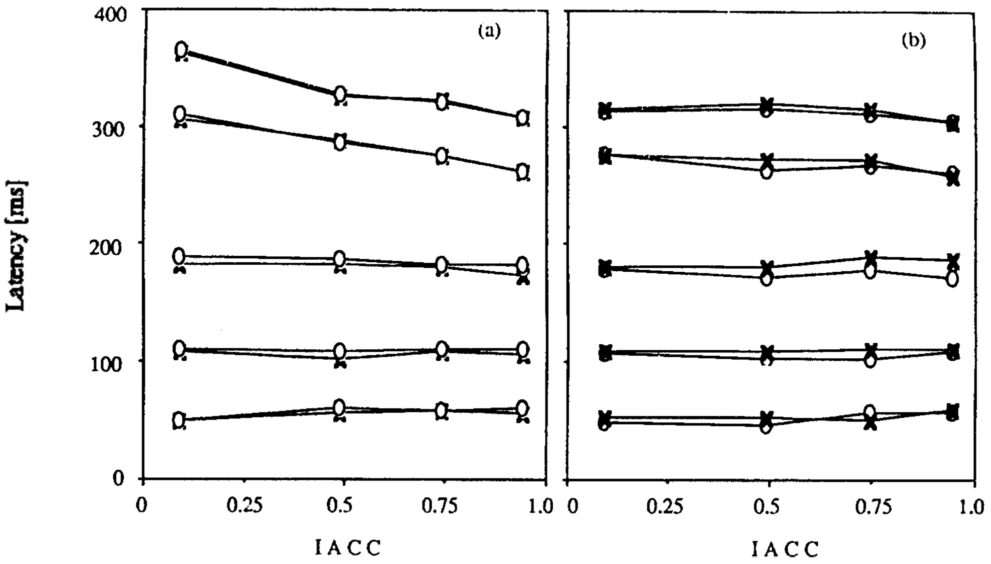

Figure 4. Mean latencies as a function of IACC(8 subjects) × : Left Hemispere, ○ : Right hemisphere

(a) Latencies of the test sound field. The latency of N_2 decreases as IACC increases.

(b) Latencies of the reference sound field with IACC=0.95(as a function of IACC of the paired test sound field).

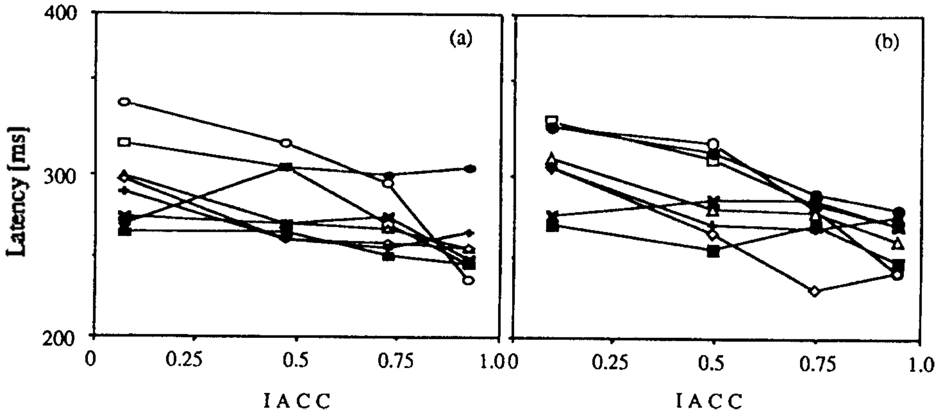

Figure 5. N_2 latency versus IACC for each subiect. (a) Left hemishpere, (b) Right hemisphere.

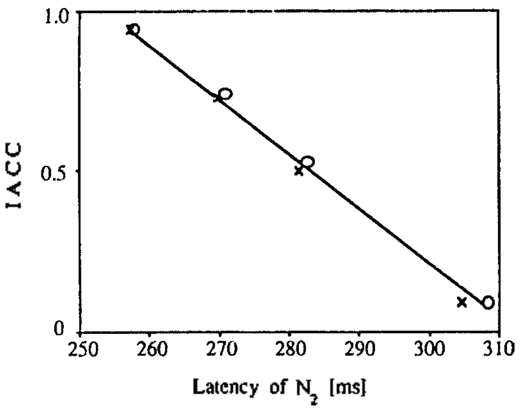

Figure 6. Linear relationship between IACC and N_2 latency(correlation coefficient=−0.99 at 1% significance level). × : Left hemisphere, ○ : Right hemisphere − : Regression line

Ⅳ. DISCUSSION AND CONCLUSIONS

In the amplitude components of AER, no systematic change in relation to IACC was observed. However, the hemispheric difference for noise stimulus was found, in which the amplitudes for the right hemisphere were greater than those for the left. This result coincides with the result of studies which have identified the right hemispheric dominance against noise or non-verbal stimuli[9][14] In anplitudes $A(P_2\text{-}N_2)$ and $A(P'_2\text{-}N'_2)$, larger values in the left hemisphere than in the right were observed. But, this is not yet well explained.

An analysis of the latency showed no changes due to IACC in P_1, N_1 and P_2 peaks of AER. However, latencies in N, P peaks of AER linearly decreases with increasing IACC(Fig. 6). Such auditory evoked responses to IACC may relate to the subjective diffuseness to the sound field. The latencies of AER for the reference sound are independent on IACC of the test sound : therefore, the latency for the test sound only relates sufficiently well to the subjective diffuseness due to the relative binaural processing.

The behavior of latency to the test sound was confirmed by a further experiment in which the single test stimulus with a constant IACC was delivered, i.e., the behavior of latency versus IACC was also identified to be similar to that of the present study in spite of the different way of presenting the stimulus[15][17].

In the test result for subjective diffuseness, the scale value is approximately expressed in terms of the 3/2 power of IACC (see Fig.3 in Reference 5). Such a nonlinear evaluator of subjective diffuseness must be assumed to exist somewhere in the upper apart of the brain.

The binaural process, called localization or lateralization, mainly depends on the intensity difference of the stimuli at the two ears and the time difference of arrival at the two ears. In our case, however, since the stimuli to the two ears were kept equal in intensity and time difference, this binaural interaction model can not well explain the subjective diffuseness. The latency behavior suggests the existence of a set of neurons or a mechanism in the auditory-brain system which respond the interaural cress-correlation of sound field.

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