Investigations on Cerebral Hemisphere Activities Related to Subjective Preference of the Sound Field, Published for 1983 - 2003

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Theory of subjective preference of the sound field in a concert hall is described for a number of subjects, based on the model of human auditory-brain system. The model consists of the autocorrelation function (ACF) mechanism and the interaural crosscorrelation function (IACF) mechanism for signals arriving at two ear entrances, and the specialization of human cerebral hemispheres [Ando, Concert Hall Acoustics, Springer-Verlag, Heidelberg, 1985; Architectural Acoustics, AIP/Springer-Verlag, New York, 1998]. It is considered that subjective preference is the most primitive response of living creatures, and the direction of preference may be maintaining life. It is assumed that information corresponding to subjective preference of sound fields can be found in brain activities, such as in auditory-brainstem response (ABR), slow vertex responses (SVR), electroencephalography (EEG) and magnetoencephalography (MEG). In fact, this has been discovered in the effective duration, τ_e, ACF of the alpha waves in EEG and MEG related to subjective preference. The temporal factors of sound fields such as initial time delay gap between the direct sound and the first reflection (Δt_1) and subsequent-reverberation time (T_{sub}) are deeply associated with the left hemisphere. And the spatial factors such as magnitude of interaural cross-correlation (IACC) and listening level (LL) are associated with the right. Surprisingly, individual differences in subjective preference appears in the difference of τ_e of the alpha wave in EEG and MEG. Large individual differences of subjective preference are observed mainly in temporal factor Δt_1 and T_{sub} and LL, but not in the typical spatial factor IACC. Individual differences in LL may be related to individual hearing levels. These evidences support the theory of subjective preference described based on the model of human auditory-brain system. This theory may be applied for individual level of subjective preference as well.

Keywords: subjective preference, autocorrelation functions of the alpha waves, auditory-brainstem response (ABR), slow vertex responses (SVR), electroencephalography (EEG), magnetoencephalography (MEG), model of auditory-brain system, specialization of cerebral hemispheres

GLOSSARY OF SYMBOLS (THE NUMBER IN THE BRACKET SIGNIFIES THE NUMBER OF EQUATION, WHICH MAINLY CONCERNED WITH THE DEFINITION)

A — Total amplitude of reflections, (8)

A_n — Amplitude of n-th reflection, A_0 is the amplitude of the direct sound, and A_1 is that of the first reflection or the single reflection

$A(P-N)$ — Peak-to-peak amplitude of SVR

$A_{IV,l}$, $A_{IV,r}$ — Amplitudes of ABR wave IV obtained on the left and right side, respectively, in auditory pathway

A_V — Averaged amplitudes of ABR wave V, for those of V_l and V_r obtained on left and right side, respectively, in auditory pathway

A_n — Pressure amplitude of n-th reflection determined by the (l/r) law, A_0 (n = 0) being unity, n = 1, 2, …, (8)

$C_{l,r}(t)$ — Transfer function for vibration of left and right bone chains, from the eardrum to the oval window, including transformation factors in vibration motion at the eardrums, Fourier transform of $c_{l,r}(t)$, Fig. 1

$c_{l,r}(t)$ — Impulse responses for vibration of left and right bone chains, from the eardrum to the oval window, including transformation factors in vibration motion at the eardrums, Fig. 1

d_0 — Distance between the sound source and a

a)Now at 1-10-27 Yamanokami, Kumamoto 862-0915 Japan listener for the direct sound

d_1 — Distance between the sound source and a listener for the path of the first reflection

$E_{l,r}(\omega)$ — Transfer function of left and right external canals, from the ear entrances to the eardrum, Fourier transform of $e_{l,r}(t)$, Fig. 1

$e_{l,r}(t)$ — Impulse responses of left and right external canals, from the ear entrances to the eardrums, Fig. 1

F — Number of stimuli, (B.6)

f — 10^{-15}; other examples, m: 10^{-3}; μ: 10^{-6}; n: 10^{-9}; p: 10^{-12}, Fig. 18a

$H_{l,r(r/r_0,\omega)}$ — Head-related transfer function (HRTF) from a source position to the left and right ear-entrances, Fourier transform of $h_{l,r(r/r_0,\omega)}$, Fig. 1

$h_{l,r(r/r_0,\omega)}$ — Head-related impulse responses from a source position to the left and right ear-entrances, Fig. 1

IACC — Magnitude or maximum value of the IACF in the maximum delay range less than 1 ms, Fig. 3

$I_{l,r}(x')$ — Sharpening in the cochlear nuclei corresponding to roughly the power spectra of input sound signal

k — Constant around 30, (3)

Left — Response on the left hemisphere.

N_m — Latencies at the m-th minima of SVR, m = l, 2, 3, Table 1., Fig. 10

p(t) — Source sound signal, (4), Fig. 1

$p'_{l,r}(t)$ — Sound pressures at the left and right ear entrances, (4)

P — Normalized physiological magnitude corresponding to the IACC, (6)

P(B>A) — Probability that a stimulus A is preferred to another stimulus B, (B.1)

P_m — Latencies at the m-th maxima of SVR, m = l, 2, ,… , Table 1., Fig. 10

r — Correlation coefficient, Fig. 20

Right — Response on the right hemisphere

s(t) — Ear sensitivity expressed in the time domain, (4), for practical applications the impulse response of the A-weighting filter correspondingto ear sensitivity, (4); $p'_{l,r}(t) = p_{l,r}(t) * s(t)$

t — Time [s]

T — Time interval [s] (1), (3), (4)

T — Tesla: unit of a magnetic flux density, 1T = 1Wb/m^2, Fig. 18a

T3, T4 — Positions of sensors on the left and right auditory cortexes, respectively

T_{sub} — Subsequent reverberation time defined by the decay rate to decrease to 60dB just after early reflections [s], (= T_{60})

$[T_{sub}]_p$ — Calculated preferred subsequent reverberation time [s], (9)

$V_{l,r}(x,w)$ — Wave forms of the basilar membranes, where x the position along the basilar membrane measured from the oval window, Fig. 1

W_{IACC} — Width of the IACC or width of the IACF around the tIACC, which depends on the spectrum of the source signal, Fig. 3

$<X_d>$ — Averaged scale value (SD), (B.2)

α — Alpha (wave)

α(t) — Alpha wave as a function of time, Fig. 18a.

Δt_1 — $= (d_1 - d_0)/c$ [s]; Initial time delay gap between the direct sound and the first reflection

$[\Delta t_1]_p$ — Calculated preferred initial time delay gap between the direct sound and the first reflection [s], (7)

ϕ_1 — Amplitude at the first peak at the delay τ_1 in ACF, $\phi_p(\tau)$, corresponding to the pitch strength

$\phi_{lr}(\tau)$ — Normalized IACF, (5), Fig. 3

$\phi_p(\tau)$ — Normalized ACF, (2), Fig. 2

$\Phi_{ll}(\sigma)$, $\Phi_{rr}(\sigma)$ — Autocorrelation function mechanisms in the left and right auditory-pathway, respectively, Fig. 1.; the symbol (+) in Fig. 1. signifies that signals to be combined

$\Phi_{ll}(0)$, $\Phi_{rr}(0)$ — ACFs at the origin of time corresponding to averaged sound energies arriving at the left ear and right ear, respectively, (5)

$[\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}$ — Geometrical mean of sound energies arriving at the left ear and at the right ear

$\Phi_{lr}(\nu)$ — Interaural crosscorrelation function mechanisms, Fig. 1

$\Phi_{lr}(\tau)$ — Interaural crosscorrelation function, (4)

$\Phi_p(\tau)$ — Autocorrelation function (ACF), (1)

$\Phi_p(0)$ — Sound energy given at the origin of time of $\Phi_p(\tau)$, $\tau = 0$, (1)

λ — Poorness of fit for the model of obtaining the scale value of a single individual, (B.7)

τ	Time delay [s], (1), (2), (4), (5)
τ_1	Delay time of the first peak in ACF, $\Phi_p(\tau)$, corresponding to the pitch of sound [s]
τ_e	Effective duration of ACF, defined by the delay time at which the envelope of the normalized ACF becomes and then remains smaller than 0.l (the ten percentile delay) [s], Fig. 2b
τ_e(IACC=0.3)	Value of ACF τ_e of the alpha wave obtained by the stimulus with IACC = 0.3 corresponding to a large spatial subjective diffuseness, Fig. 7
τ_e(IACC=0.95)	Value of ACF τ_e of the alpha wave obtained by the stimulus with IACC = 0.95 corresponding to a small spatial subjective diffuseness, Fig. 7
$(\tau_e)_{min}$	Minimum value of τ_e obtained by analyzing the running ACF of a piece of source signal, $\phi_p(\tau)$ [s]
τ_{IACC}	Interaural delay time at which IACC is defined [s], Fig. 3
α	Alpha (wave)
ω	Angular frequency (= 2πf, f being the frequency [Hz])
ξ	Horizontal angle of sound incidence to a listener [°], (Fig. 4., 5., and 6.)

Abbreviations

ABR	Auditory brainstem response
ACF	Autocorrelation function
EEG	Electroencephalogram
fMRI (FMRI)	Functional Magnetic Resonance Imaging
HRTF	Head-related transfer function
IACF	Interaural crosscorrelation function
LL	Binaural listening level, [dB(A)]
MEG	Magnetoencephalography
SD	Scale value
SL	Sensation Level
SVR	Slow vertex response
PWL	Power level (of sound source)

1. INTRODUCTION

A theory of designing concert halls based on a model of auditory-brain system, which takes account of temporal factors and spatial factors for subjective preference of sound fields, has been proposed (Ando, 1985). “Subjective preference” has been investigated, because it is considered as the primitive response of a living creature, and its direction of judgement maintains the life of body, mind and personality. Thus, brain activities may be closely associated with subjective preference. The model consists of ACF and IACF mechanism for signals arriving at the two ear entrances, and the specialization of human cerebral hemispheres.

For the purpose of identifying the proposed model of the auditory-brain system, experiments point toward the possibility of developing a correlation between brain activities, measurable with the SVR and EEG. The subjective preference is due to the primitive response for each acoustic factor. These factors comprise two temporal factors [Δt_1 and T_{sub}] which are associated with the left hemisphere, and two spatial factors [LL and magnitude of IACF] associated with the right hemisphere. Since individual differences of subjective preference in relation to IACC in the spatial factors are small, we can determine the architectural space form of the room at first. The temporal factors are closely related to the dimensions of a specific concert hall, which can be altered to exhibit specific types of music, such as organ music, chamber music or choral works (Ando, 1998).

An attempt is made to know about how auditory and the two cerebral hemispheres modify nerve impulse responses from the cochlea. So that, not only the design such as concert halls, but also such as speech recognition, identification of environmental noise and its subjective effects, and music perception could be proceed according to guidelines derived from the model. It is remarkable that neural activities include sufficient information to obtain the ACF, probably at the lateral lemniscus. A possible mechanism for the interaural time difference and correlation processors in the time domain has been proposed (Jeffress, 1948, Licklider, 1951). It has been revealed by recording left and right ABR that the maximum neural activity (wave V) corresponds to the magnitude of the IACF (Ando et al., 1991). Also, the left and right waves $IV_{l,r}$ nearly correspond to the sound energies at the right- and left-ear entrances. In fact, the time domain analysis of the firing rate of the auditory nerve of a cat reveals a pattern of ACF rather than the frequency domain analysis (Secker-Walker and Searle, 1990). Pooled interspike interval distributions resemble the short time or the running ACF for low-frequency component. In addition, pooled interval distributions for sound stimuli consisting of the high-frequency component resemble the envelope to running ACF (Cariani and Delgutte, 1996).

Recently, we have reconfirmed by EEG and MEG that the left cerebral hemisphere is associated with Δt_1 (Soeta et.

al., 2002a; 2003) and the right cerebral hemisphere is activated by the typical spatial factors, IACC (Sato et al., 2003). The information corresponding to subjective preference (primitive response) of sound fields can be found by the effective duration of ACF of the alpha waves of both EEG and MEG. The repetitive feature of the alpha wave as measured in its ACF may be observed at the preferred condition. This evidence ensures that the basic theory of subjective preference may be applied to each individual preference as well (Ando, 1998).

The left hemisphere is mainly associated with time-sequential identification (Zatorre and Belin, 2001, Wong, 2002), and the right one is fundamentally concerned with spatial identifications. It is worth noticing that the spatial factor W_{IACC} extracted from the IACF is closely related to the spectral feature. Recently, the left-hemispheric specialization of speech signals has been reported by a number of authors using EEG and MEG (For example, Eulitz et al., 1995, Näätänen et al., 1997, Alho et al., 1998). By records of fMRI, it has been shown left hemisphere specialization for verbal and right hemisphere for nonverbal corded information (Opitz et al., 2000).

Based on the auditory-brain system, primary sensations such as pitch or missing fundamental, loudness, timbre, and in addition duration sensation are described by the temporal factors extracted from the ACF (Ando, 2002). Remarkably, the temporal factors of sound fields such as Δt_1 and T_{sun} are associated with left hemisphere (Ando et al., 1987a; Ando, 1992; Ando and Chen, 1996; Chen and Ando, 1996; Soeta et al., 2002a). And, typical spatial factor of sound fields such as IACC relating to subjective diffuseness (Ando and Kurihara, 1986) and apparent source width (ASW) as well as subjective preference (Sato and Ando, 1996; Ando et al., 2000) is associated with the right hemisphere (Ando and Hosaka, 1983; 1985; Ando et al., 1987b; Ando, 1992; Ando, 1998; Sato et al., 2003).

It is quite possible that not only for acoustic design of concert halls and opera houses, but this kind of concept may be applied for a design of physical environment. Both spatial and temporal factors are explicitly considered to a general theory of physical environmental design including vision based on the brain activities (Soeta et al., 2002b; 2002c; Okamoto et al., 2003). The ideas of temporal design come out to publish Journal of Temporal Design in Architecture and the Environment founded in 2001 (http://www.jtdweb.org/).

2. MODEL OF AUDITORY-BRAIN SYSTEM

2.1 Model

The auditory-brain model which has been proposed in concert hall acoustics (Ando, 1985) is shown in Fig. 1. In this figure, $\Phi_{ll}(\sigma)$ and $\Phi_{rr}(\sigma)$ are ACF mechanisms in the left and right auditory-pathways, $\Phi_{lr}(\nu)$ is the IACF mechanisms. It is worth noticing from investigations since 1982 (Ando, 1998) that a spatial factors (IACC and binaural listening level, LL) of sound fields extracted from the IACF mechanism, and temporal factors (Δt_1 and T_{sub}) of sound fields extracted from the ACF mechanisms dominantly process in different hemispheres, labeled r and l, respectively.

The method of calculating physical factors, which may be extracted from the ACF and the IACF of sound signal arriving at two ear-entrances, is described in Section 2.3.

2.2 Physical System in the Outer and Inner Ear

First of all, one is interested in the fact that the human ear sensitivity to a sound source in front of the listener is essentially formed by the physical system from the source point to the oval window of the cochlea (see APPENDIX; Ando, 1985; 1998). The transfer functions in such a cascade system consisting of the human head and pinna, the external canal and the eardrum and the bone chain are shown in Fig. 1. For the sake of convenience, the efferent pathways are ignored in this model. The A-weighting network may be utilized for practical purposes representing the transfer function of the physical system in both the outer and the inner ear. Determination of s(t) in term of h(t), e(t) and c(t) has been carefully described in APPENDIX A.

2.3 Temporal and Spatial Factors Extracted from ACF and IACF Analyses

Primary sensations and spatial sensations as well as subjective preference for sound fields are well described by both temporal and spatial factors extracted from ACF and IACF, respectively.

2.3.1 Factors extracted from the ACF for the signal arriving at the ear entrance

The ACF is defined by

$$\Phi_p(\tau) = \frac{1}{2T}\int_{-T}^{+T} p'(t)\,p'(t+\tau)\,dt \qquad (1)$$

where $p'(t) = p(t)*s(t)$, s(t) being the ear sensitivity, which is essentially formed by the transfer function of the physical

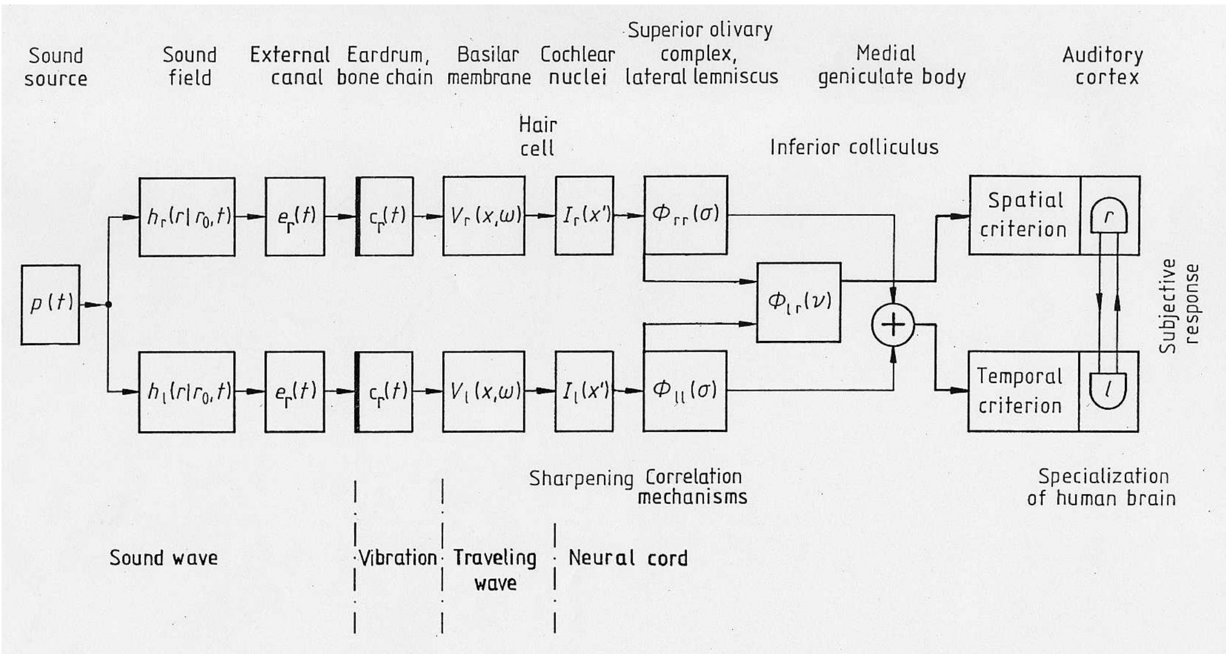

Fig. 1. Model of processors in the auditory-brain system for subjective responses. p(t): source sound signal in the time domain; $h_{l,r}(r/r_0,t)$: head-related impulse responses from a source position to the left and right ear-entrances; $e_{l,r}(t)$: impulse responses of left and right external canals, from the left and right ear-entrances to the left and right eardrums; $c_{l,r}(t)$: impulse responses for vibration of left and right bone chains, from the eardrums to oval windows, including transformation factors into vibration motion at the eardrums: $V_{l,r}(x,\omega)$: travelling wave forms on the basilar membranes, where x the position along the left and right basilar membrane measured from the oval window; $I_{l,r}(x')$: sharpening in the cochlear nuclei corresponding to roughly the power spectra of input sound, i.e., responses of a single pure tone ω tend to approach a limited region of nuclei. These activities may be enough to convert into activities similar to the ACF; $\Phi_{ll}(\sigma)$ and $\Phi_{rr}(\sigma)$: ACF mechanisms in the auditory-pathways, the symbol (+) signifies that signals are combined; $\Phi_{lr}(\nu)$: IACF mechanisms (Ando, 1985); r and l: specialization for temporal and spatial factors of the left and right human cerebral hemispheres, respectively. Temporal sensation and spatial sensations may be made by the left and right hemisphere, respectively, and the total subject response such as subjective preference of the sound field may be made by both hemispheres (Ando, 2002).

system to the oval of the cochlea (APPENDIX A). Rigorously, the individual sensation represented by s(t) is different, however; s(t) may be chosen as the impulse response of an A-weighted network for practical use. The ACF and the power density spectrum mathematically contain the same information.

There are four significant factors, which can be extracted from the ACF:
(i) The energy represented at the origin of the delay is given by $\Phi(0)$;
In the fine structure including peaks and delays (Fig. 2a), for instance, ϕ_1 and τ_1 are the delay time and the amplitude of the first peak of ACF. These factors are closely related to the pitch including the phenomenon of missing fundamental and the pitch strength. Then, there are τ_n and ϕ_n being the delay time and the amplitude of the n-th peak (n > 1). However, there are certain correlations between τ_n and τ_{n+1}, and between ϕ_n and ϕ_{n+1}, Thus, the significant factors are:
(ii) τ_1; and
(iii) ϕ_1.
(iv) Effective duration of the envelope of the normalized ACF, τ_e, which is defined by the ten-percentile delay and which represents a repetitive feature or reverberation containing the sound source itself. The normalized ACF is defined by

$$\phi_p(\tau) = \Phi_p(\tau)/\Phi_p(0) \qquad (2)$$

As is shown in Fig. 2b, τ_e is obtained by fitting a straight line for extrapolation of delay time at –10 dB, if the initial envelope of ACF decays exponentially. It is remarkable that these temporal factors may well describe four primary sensations, loudness, pitch, timbre and duration (Ando, 2002).

2.3.2 Temporal Window in Analysis of the Running ACF

In the analysis of the running ACF, so called the "auditory-

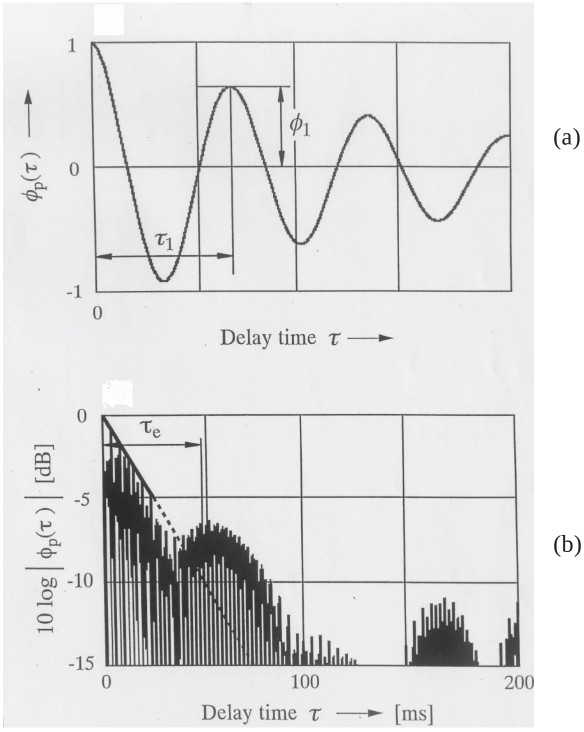

Fig. 2. Definition of temporal factors other than $\Phi(0)$ extracted from the normalized ACF of signal (a). Effective duration of the ACF, τ_e, which is defined by 10 percentile delay (−10 dB) and which is obtained practically by the extrapolation of the envelope of the normalized ACF during the decay, 5 dB initial (b) (Ando, 1998).

temporal window” 2T in Equation (1) must be carefully determined. Since the initial part of ACF within the effective duration τ_e of the ACF contains important information of the signal, the recommended signal duration (2T) to be analyzed is given approximately by

$$(2T)_r = k(\tau_e)_{min} \text{ [s]} \tag{3}$$

where $(\tau_e)_{min}$ is the minimum value of τ_e obtained by analyzing the running ACF, and the k selected is around 30 (Mouri et al., 2001). It is worth noticing that the minimum value of τ_e may determine the most preferred temporal factors (Section 3.1; Ando et al., 1989). Thus, it is considered that an ACF processor in the auditory pathway works accurately in its delay range within the value of τ_e, in which important information of sound signals may contain.

2.3.3 Factors extracted from the IACF for signals arriving at left and right ear entrances

The IACF is given by

$$\Phi_p(\tau) = \frac{1}{2T}\int_{-T}^{+T} p'(t)\,p'(t+\tau)\,dt \tag{4}$$

where $p'_{l,r}(t) = p(t)_{l,r} * s(t)$, $p(t)_{l,r}$ being the sound pressure at the left- and right-ear entrances. The normalized IACF is given by

$$\phi_{lr}(\tau) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2} \quad -1 \text{ ms} < \tau < +1 \text{ ms} \tag{5}$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are ACFs ($\tau = 0$, or sound energies arriving at the left- and right-ear entrance, respectively. Spatial factors extracted from the IACF are defined in Fig. 3 (Ando, 1998).

When a sound source is moving in the horizontal direction, we must know a suitable “temporal window” 2T in analyzing the running IACF, which corresponds to the moving image of localization. The range of such a moving image can be described by the range of τ_{IACC} extracted from the IACF. It is obvious that the range of τ_{IACC} is disappeared, when the integration interval 2T is too long, and the value of τ_{IACC} may not be determined, when 2T is too short. For a sound source moving sinusoidally in the horizontal plane with less than 0.2 Hz, 2T may be selected from 30 to 1000 ms. And, when a sound source is moving below 4.0 Hz, 2T = 30 - 100 ms is acceptable (Mouri et al, submitted). In order to obtain reliable results, it is recommended for such a temporal window for such the spatial factor covering a wide range of movement velocity in the horizontal localization may be fixed about 30 ms. For the sound source fixed on the stage in a concert hall, for example, the values of 2T may be selected longer than 1.0 s in the measurement of the IACF at each audience.

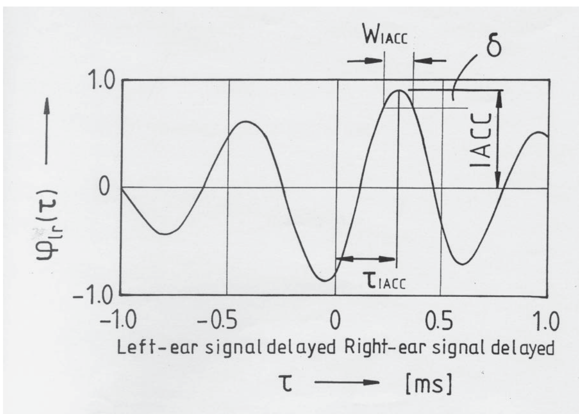

Fig. 3. Definition of spatial factors, other than the binaural LL or energy given by the denominator in Equation (5), IACC, τ_{IACC} and W_{IACC} extracted from the normalized IACF (Ando, 1998).

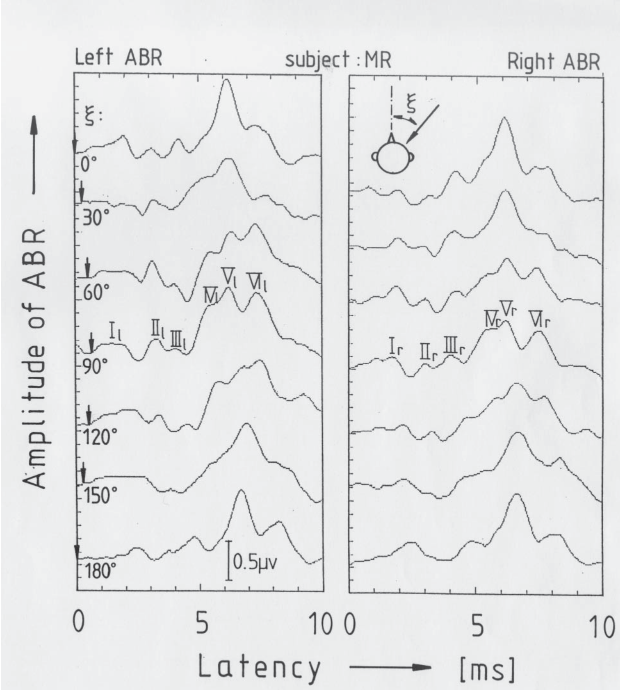

Fig. 4. Examples of ABR, wave I through wave VI, obtained between the vertex and left- and right-mastoids, as a parameter of the horizontal angle of sound incidence. A short pulse (50 μs) was applied to a loudspeaker of a wide frequency range of 100 Hz to 10 kHz. The abscissa is the time relative to the first arrival time at the right ear entrance. Arrows indicate the arrival time, depending upon the sound source location of the right hand side of the subject, and the null amplitude of ABR (Ando et al., 1991).

The spatial factors extracted from the IACF are:

(i) the sound energy given by $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ measured at the two-ear entrances;

(ii) IACC: the magnitude or maximum value of the IACF for the maximum possible interaural delay time, -1 ms $< \tau <$ + 1 ms;

(iii) W_{IACC} depending on the frequency component of source signals; and

(iv) τ_{IACC} as the interaural delay time.

It is worth noticing that spatial sensation, such as subjective diffuseness (Ando and Kurihara, 1986); the ASW may be described by the four spatial factors (Sato and Ando, 1996; Ando et al., 1999; Ando et al., 2000). Also, sound localization in the horizontal plane and loudness due to the binaural summation of the sound energy may well be described by these spatial factors (Ando, 2002).

2.4 Auditory-Brainstem Responses (ABR) Corresponding to Energies at both Ears and IACC

Examples of recording ABR as a parameter of the horizontal angle of sound incidence are shown in Fig. 4. It is seen that waves I - VI from the vertex and the right mastoid differ in amplitude as indicated by each curve. Quite similar ABR-data among the four subjects who participated were obtained, and data for the four subjects (23 ± 2 years of age, male) were averaged.

A possible mechanism has been found for the IACC in the auditory pathways in judging subjective preference (Ando, 1985; 1998) and subjective diffuseness (Ando and Kurihara, 1986). The left and right ABR were recorded in order to justify such a mechanism for the spatial information that might exist in the auditory pathways (Ando et al., 1991).

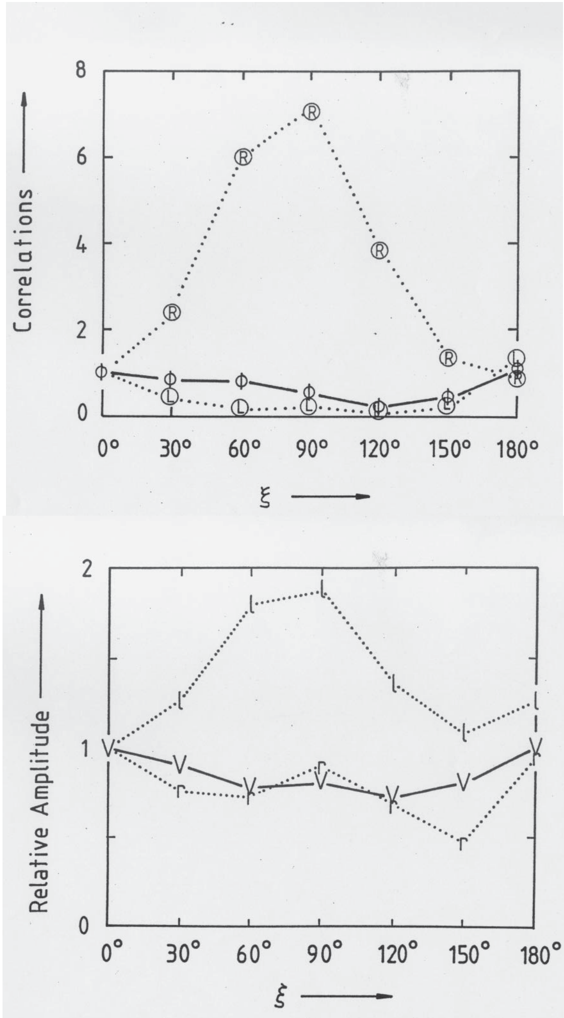

Fig. 5. Energies and interaural correlation of sound signals measured at the ear entrances, (L): $\Phi_{ll}(0)$ measured at the left-ear entrance; (R): $\Phi_{rr}(0)$ measured at the right-ear entrance, and Φ: maximum value of IACF (a). ABR amplitudes of wave $VI_{l,r}$ is averaged amplitude of waves IV_l, and that of waves IV_r. V: averaged amplitudes of waves V_l and V_r, because V_l and V_r had a similar behavior as a function of the horizontal angle ξ (b) (Ando et al., 1991).

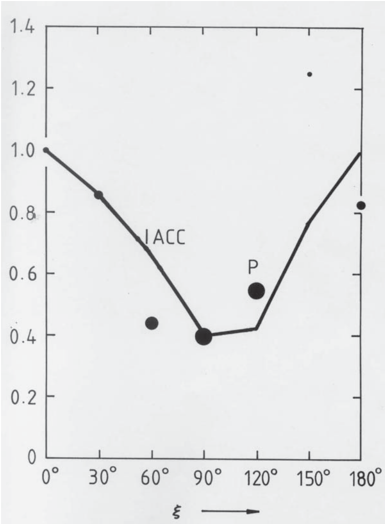

Fig. 6. Comparison between values of the IACC measured at the two ear entrances, and P value calculated by Equation (6) with the amplitude of waves $IV_{l,r}$ and averaged amplitude V (Ando et al, 1991).

Figures 5a and b show values of the magnitude of IACF and the energies at the ear entrances given by ACFs at the time origin. These were measured at the two ear entrances of a dummy head as a function of the horizontal angle after passing through the A-weighting networks.

The averaged amplitudes of waves IV (left and right) and averaged amplitudes of wave V that were both normalized to the amplitudes at the frontal incidence ($\xi = 0°$) are shown in Fig. 5b. Even with a lack of data at $\xi = 0°$, similar results could be obtained when the amplitudes were normalized to those at $\xi = 180°$. Although we cannot make a direct comparison between the results in Fig. 5a and 5b, it is interesting to point out that the relative behavior of wave IV_l in Fig. 5b is similar to $\Phi_{rr}(0)$ measured at the right-ear entrance r as shown in Fig. 5a. Also, the relative behavior of wave IV_r is similar to that of $\Phi_{ll}(0)$ at the left-ear entrance l. In fact, amplitudes of wave IV (left and right) are proportional to $\Phi_{xx}(0)$, (x = r, l, respectively), due to the interchange of signal flow. The behavior of wave V is similar to that of the maximum value, $|\Phi_{ll}(\tau)|_{max}$, $|\tau| < 1$ ms. Since the correlation have the dimensions of the power of the sound signals, i.e., the order of A^2, the IACC defined by Equation (5) may correspond to

$$P = \frac{A_V^2}{\left[A_{IV,r} A_{IV,l}\right]}, \tag{6}$$

where A_V is the amplitude of the wave V, which may be reflected by the "maximum" neural activity ($A_V^2 \approx |\Phi_{lr}(\tau)|_{max}$) at the inferior colliculus. Also, $A_{IV,r}$ and $A_{IV,l}$ is amplitudes of wave IV of the right and left, respectively. The results obtained by Equation (5) are plotted in Fig. 6. It is clear that the relative behaviors of IACC and P are in good agreement, except for the value of P at $\xi = 150°$ at which only a single datum for A_{IV} was obtained, with only a single subject. The values exceeding unity are caused by error in the measurements. Obviously, a high correlation between the values of IACC and P is achieved, i.e., 0.92 ($p < 0.01$).

3. BRAIN ACTIVITIES CORRESPONDING TO SUBJECTIVE PREFERENCE OF THE SOUND FIELD

3.1 Four Orthogonal Factors for Subjective Preference of Sound Fields

Before going into analyses of brain activities corresponding to subjective preference, we discuss the most preferred conditions with global subjects obtained by a series of paired-comparison tests, which may be described by four orthogonal

Table 1. Hemispheric specialization determined by analyses of AEP (SVR), EEG and MEG.

Factors changed	AEP (SVR) $A(P_1–N_1)$	EEG, ratio of ACF τ_e value of α-wave	MEG, ACF τ_e value of α-wave
Temporal			
Δt_1	L > R (speech)	L > R (music)	L > R (speech)
T_{sub}	–	L > R (music)	–
Spatial			
LL	R > L (speech)	–	–
IACC	R > L (vowel /a/) R > L (band noise)	R > L (music)	–

factors: two temporal and two spatial factors (Ando, 1983; 1985). Here, the classification of temporal and spatial factors is made by the specialization of human cerebral hemispheres as indicated in Table 1.

Two temporal factors (Left hemisphere):

(1) The most preferred Δt_1, $[\Delta t_1]_p$, is expressed by

$$[\Delta t_1]_p \approx [1 - \log_{10}A](\tau_e)_{min} \quad (7)$$

where $(\tau_e)_{min}$ is the minimum value of the τ_e of running ACF of the source signal, and A is the total amplitude of reflections, given by

$$A = \left(\sum_{n=1}^{\infty} A_n\right)^{1/2}, \quad (8)$$

A_n being the pressure amplitude of the n-th reflection, n = 1, 2, …

(2) The most preferred T_{sub}, $[T_{sub}]_p$, is expressed approximately by

$$[T_{sub}]_p \approx 23(\tau_e)_{min}. \quad (9)$$

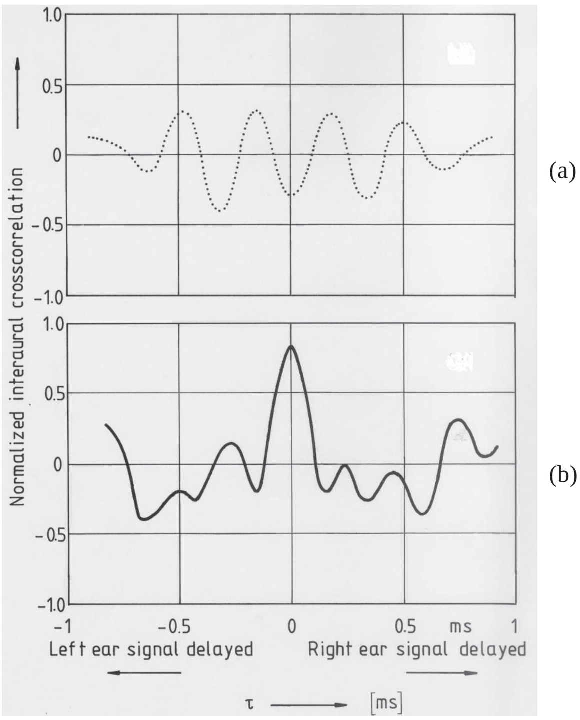

Fig. 7. Measured IACF of the two different spatial stimuli. Stimulus A with IACC = 0.41 of "diffuse" sound field which was reproduced by applying incoherent speech signals /a/ with the time delay of 300 ms to two loudspeakers as shown at upper left in Fig. 8, Stimulus B with IACC = 0.83 of "frontal" sound incidence to a listener which was reproduced by the loudspeakers without any time delay (Ando and Hosaka, 1983; 1985).

Two spatial factors (Right hemisphere):

(3) The typical spatial factors of the sound field are the IACC (Fig. 3). The consensus-preference is obtained at a small value of the IACC, so that signals arriving at both ears should be dissimilar. However, the peak value of the IACF must be maintained at the origin of the delay time, i.e.,

$$\tau_{IACC} = 0, \quad (10)$$

so that the sound field should be well balanced.

(4) The LL is calculated at each seat, such as

$$LL = PWL + 10\log(1+A) - 20\log d_0 - 11 \text{ [dB]} \quad (11)$$

where PWL is the power level of the sound source, and d_0 is the distance between the source and a listener that is related to the direct sound. The most preferred LL, $[LL]_p$, is assumed to be at the center part of seating area in the acoustic design, because performers can to some extent control PWL to the listeners.

It is worth noticing that large individual differences in the subjective preference judgments were observed for the temporal factor Δt_1, T_{sub}, and LL due to the individual hearing level. However, almost all of subjects tested over 500 preferred the sound fields with a small value of IACC.

3.2 Slow Vertex Responses (SVR) in Change of Four Orthogonal Factors

3.2.1 Preliminary Study of SVR in Change of IACC

In order to examine responses corresponding to subjective preference and the hemispheric difference with respect to the appreciation of spatial sensation, dynamic differences were obtained through auditory evoked potential (SVR) when a pair of stimuli with vowel /a/ changing IACC were presented. This experiment was first performed in 1982 (Ando and Hosaka, 1983; 1985). This method enable us to make a precise comparison of the dynamic responses in SVR over both hemispheres of each stimulus and is meaningful in connection with the results obtained from the paired comparison tests of subjective preference.

Measured IACF of the vowel /a/ are shown in Fig. 7. The stimulus (a) is the low IACC value (0.41) of the sound field with clearly perceived subjective diffuseness. The stimulus (b) is the high IACC value (0.83) with perception of a frontal

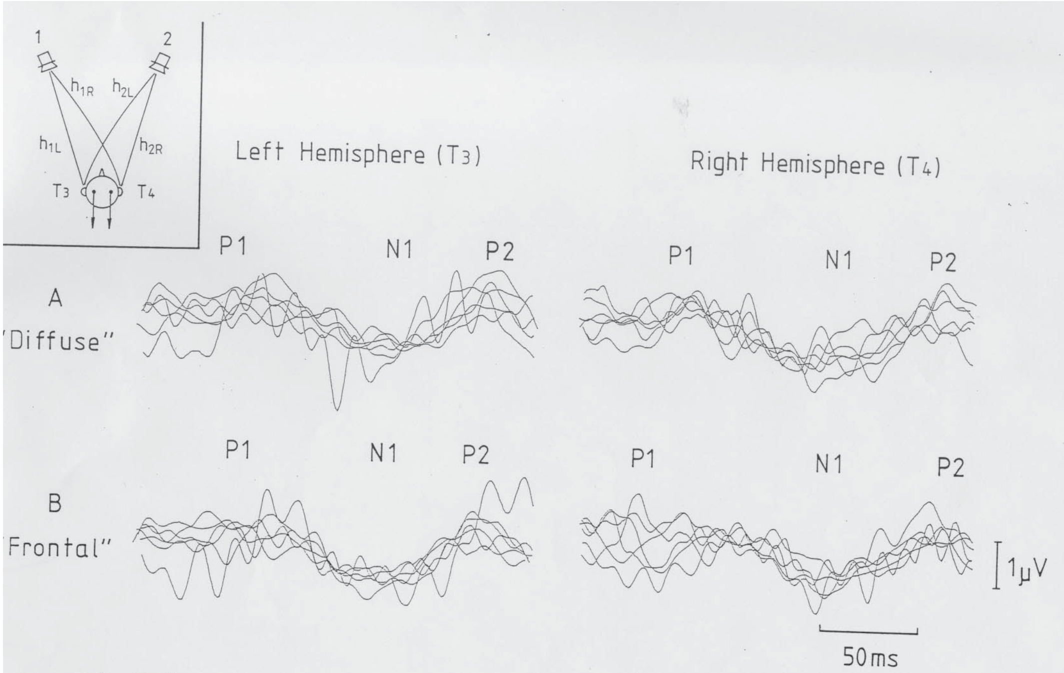

Fig. 8. Examples of SVR averaged for 128 times over the left and right hemisphere (T3 and T4) of a single subject I under alternative presentation of stimuli A and B with speech /a/ of 100 ms. Clearly, large latency differences (P_2–P_1) may be found on the right hemisphere when the paired stimuli A and B were presented (Ando and Hosaka, 1983; 1985).

sound direction which corresponds to a peak at $\tau = 0$. Since the chosen source signal is a part of continuous speech vowel /a/, even the running IACF is invariable. The stimuli were 100 ms in duration without any click, and the peak sound pressure level was set at 70 dBA. The interstimulus interval was 300 ms. The electrical responses were obtained from the left and right temporal area (T3 and T4, respectively) according to the International 10 - 20 System (Jasper, 1958). Prior to the test, each subject was asked to abstain from smoking and from drinking of any kind of alcoholic beverage for about 12 hours.

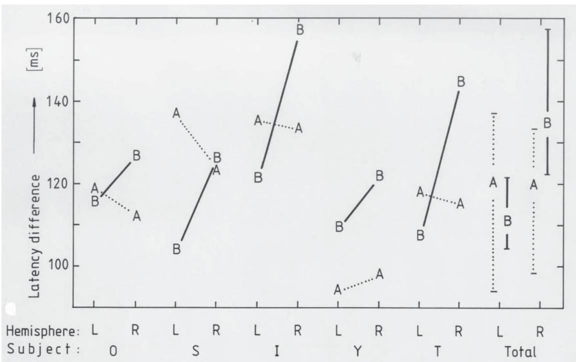

Fig. 9. Latency differences (P_2–P_1) recorded from T3 on the left and T4 on the right hemispheres under dynamic presentation of two spatial stimuli A and B. "Total" in the horizontal axis signifies the range of latencies for five subjects, O, S, I, Y and T (Ando and Hosaka, 1983; 1985).

Dynamical differences due to the two spatial stimuli were clearly observed in amplitude and latency-differences. For example, recorded SVRs from a subject I are shown in Fig. 8. A large latency difference (P_2–P_1) over the right hemisphere under alternative presentation of the spatial stimuli is found. The similar tendencies for all of five subjects may be demonstrated in Fig. 9. This may be interpreted as supporting the hypothesis of asymmetry of hemisphere functioning to the spatial factor. The latency-differences from the right hemisphere were clearly increased as the IACC increased ($p < 0.01$). This may relate to subjective diffuseness, and thus subjective preference.

3.2.2 SVR Corresponding to Subjective Preference in Change of Δt_1, SL and IACC

In order to compare results of SVR with the subjective preference obtained by paired-comparison tests, a reference stimulus was first presented and then the adjustable test stimulus was presented. Such pairs of stimuli were presented alternately 50 times and the SVR was recorded. The reference electrodes were located on the right and left earlobes and were connected together. Fig. 10 shows examples of the SVR amplitude obtained by averaging the 50 responses for a single

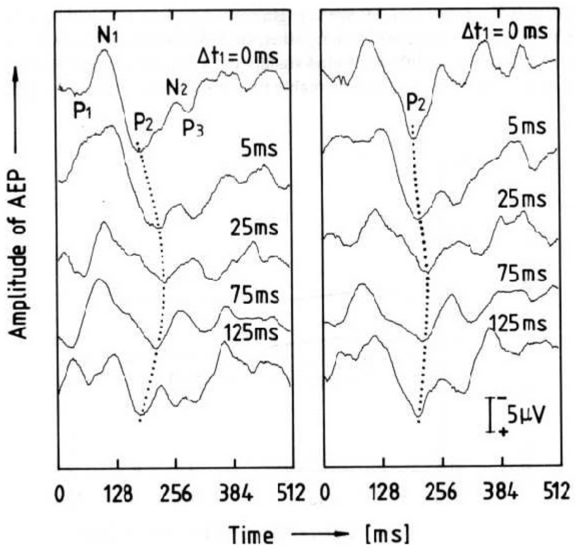

Fig. 10. Examples of averaged SVRs recorded from T3 on the left hemisphere and T4 on the right hemisphere of a single subject obtained by a continuous Japanese speech under alternative presentation with different Δt_1. Dotted lines are the loci of P_2 latency for the Δt_1. The upward direction indicates negativity. (a) Left hemisphere; (b) Right hemisphere (Ando et al., 1987).

subject, as a parameter of the Δt_1. The amplitude of the reflection was the same as that of the direct sound $A_0 = A_1 = 1$. The source signal was a fragment of a continuous speech (Japanese) "ZOKI-BAYASHI" (meaning a grove or a copse) of 0.9 s. The reference sound field was only the direct sound without any time delay, and the total sound pressure levels were kept constant in this experiment. Two loudspeakers producing the direct sound and the single reflection were located together in front of the subject, so that the magnitude of IACC could be kept at a constant value of nearly unity for all sound fields tested here.

From this Fig. 11, we can find the maximum latency at the most preferred delay time of reflection to be around 25 ms. It is interesting that such a maximum period of latency (125 ms) in delay of SVR corresponds roughly to the period of low frequency in the alpha-wave (8-13 Hz) of EEG, which is the brain activity of lowest frequency of the awakening stage indicating the “relaxation.” The most preferred Δt_1, which can be calculated by Equation (7), correesponds to the τ_e of the ACF of the continuous speech signal (Ando et al., 1987a).

Applying the paired method of stimuli similar to above of

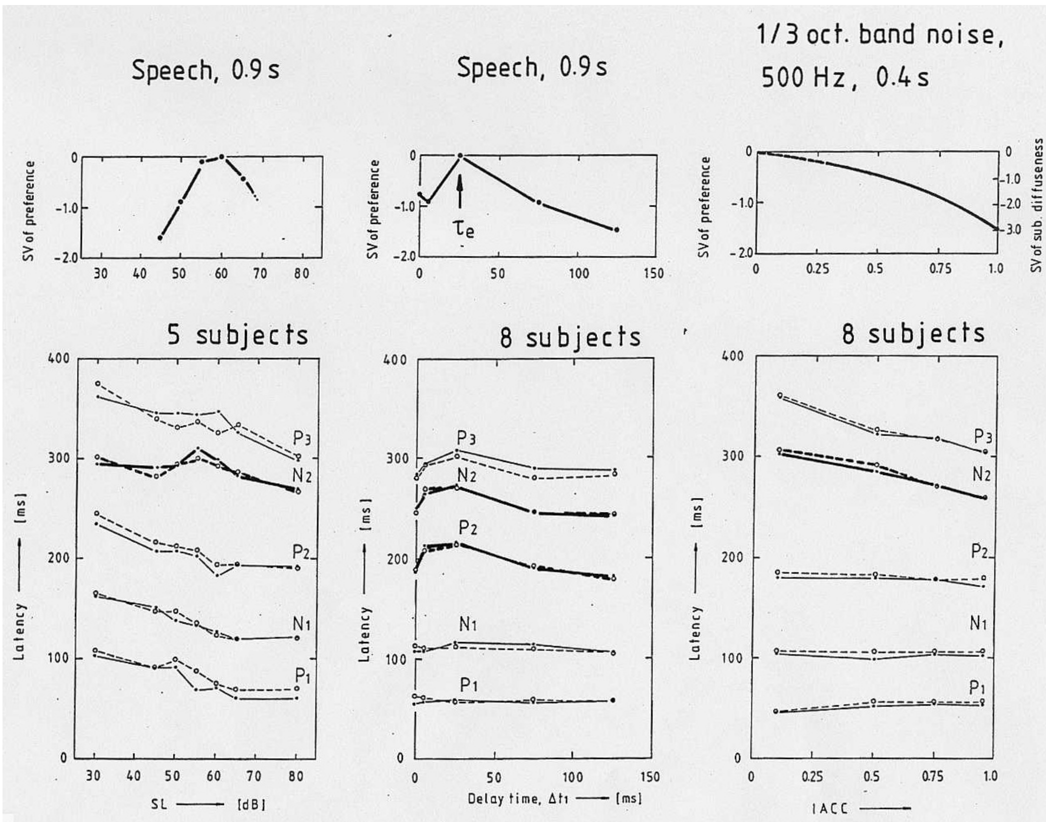

Fig. 11. Relationship between averaged latencies of SVR (lower) and subjective preference (upper) for three orthogonal factors of the sound field. In the latencies, solid lines indicate from left hemisphere and dashed lines signify from right hemisphere. Latencies as a function of the SL (Lower left); as a function of the Δt_1 (Lower center); and as a function of the IACC (Lower right) (Ando, 1998).

each subject, further series of investigations in changes of Δt_1, SL, and IACC were performed. The subjects were asked which stimulus they preferred to hear. The paired-comparison test is considered to be the most effective and simplest method for obtaining subjective preferences, because the subjects are not required to make absolute judgements. The scale values of the subjective preference of each subject were calculated according to Case V of well-known Thurstone's theory (Thurston, 1927, Gullikson, 1956). The model of Case V for all data was reconfirmed by a goodness-of-fit test (Mosteller, 1951). 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.

Figure 11 summarizes the relationship between the scale values of subjective preference and the orthogonal factors. Results of the scale value of subjective preference are indicated in the upper part of the Fig. 11, while the lower part indicates the appearance of latency components. As shown in this Fig. 11, the neural information related to subjective preference appeared commonly in an N_2-latency of 250 - 320 ms when the SL and the Δt_1 were changed. The parallel latencies at P_2, N_2 and P_3, were clearly observed as functions of the Δt_1.

In general, relatively long-latency responses are observed in the subjectively preferred range of each of the two factors. Thus, the difference of N_2-latencies over both hemispheres in response to a pair of sound fields contains almost the same information obtained from paired-comparison tests for preference as does primitive subjective response.

The right column of Fig. 11 shows the effects of varying the IACC using 1/3-octave-band noise (500 Hz). At the upper part, the scale value of the subjective diffuseness is indicated as a function of IACC. The scale value of the subjective preference also has a similar behavior plotted against IACC, when speech or music signals are presented. The information related to subjective diffuseness or subjective preference, therefore, appears in the N_2-latency, ranging from 260 - 310 ms, in which a tendency for an increasing latency while decreasing the IACC was observed for eight subjects (except for the left hemisphere of one subject). It is worth noticing that the relationship between IACC and the N_2-latency was found to be linear and the correlation coefficient between them was –0.99 ($p< 0.01$) (Ando et al., 1987a; 1987b).

Furthermore, let us look at the behavior of early latencies of P_1 and N_1. These were almost constant when the delay time Δt_1 and the IACC were changed. However, the information related to the SL or loudness may be found typically at the N_1-latency. This tendency agrees well with the results of Botte et al., (1975).

Though detailed data are not presented here, the hemispheric dominance was found for the amplitude component from 40 to 170 ms of the SVR, which may be called a specialization of the left and right hemispheres (Table 1). Early Latency differences corresponding to the SL may be found in the range of 120 to 170 ms. Consequently, it is found that the N_2-latency components in the delay range between 200 ms and 320 ms may correspond well with the subjective preference relative to the LL, the Δt_1, and, indirectly, the IACC. Since the longest latency was always observed at the most preferred condition, it is concluded that the larger part of the brain is relaxed at the preferred condition, causing the observed latency behavior to occur.

3.3 Electroencephalography (EEG) Corresponding to Subjective Preference

Thus far, we have discussed results obtained by adding auditory evoked potentials (SVR) up to 500 ms for changes in SL, Δt_1 and IACC, using short signals less than 0.9 s. However, for a wide range of T_{sub}, no useful data could be obtained from examining the SVR.

The purpose of this section is to find a distinctive feature in the continuous brain wave known as EEG following changes in the T_{sub} with a long sound-signal duration. Before going into detail, let us consider a preliminary study of the Δt_1, to reconfirm the SVR results as discussed above.

3.3.1 EEG in Change of the Delay Time of a Single Reflection

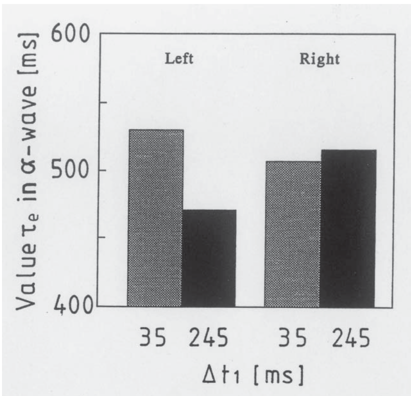

Fig. 12. Averaged value of τ_e in the alpha-brain wave range for a change of Δt_1: 35 ms of the preferred condition and 245 ms of the less preferred condition (11 subjects). Left: left hemisphere; and Right: right hemisphere (Ando and Chen, 1996).

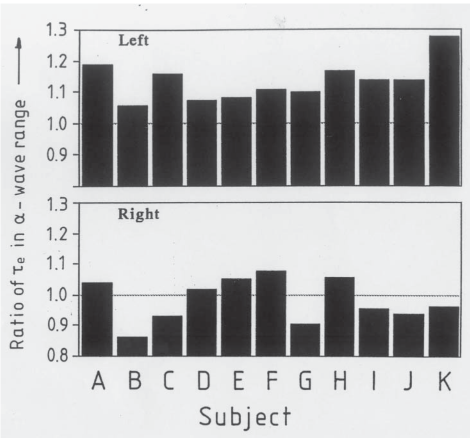

Fig. 13. Ratio of the τ_e values in the alpha-brain wave range for the change of Δt_1: 35 ms of the preferred condition and 245 ms of the less preferred condition (11 subjects, A-K). Left: left hemisphere; and Right: right hemisphere (Ando and Chen, 1996).

In this experiment, Music Motif B (Arnold: Sinfonietta of Opus 48, a 5 s piece of the 3rd movement) was selected as the sound source. The Δt_1 was alternatively adjusted to 35 ms (a preferred condition) and 245 ms (a condition of echo disturbance). The EEG of ten pairs from T3 and T4 was recorded for about 140 s, and experiments were repeated over a total of three days with 11 subjects (male students, 24 ± 2 years of age). The subject was asked to close his eyes in listening to the music during the recording of the EEG. Two loudspeakers were arranged in front of the subject. Thus, the IACC was kept at a constant value of nearly unity. The sound pressure level was fixed at 70 dBA peak, in which the amplitude of the single reflection was the same as that of the direct sound, $A_0 = A_1 = 1$. The leading edge of each sound signal was recorded at the same time for analyses of the continuous brain wave. The brain wave was recorded with sampling frequency greater than 100 Hz after passing through a filter width of 5 to 40 Hz with a slope of 140 dB/Oct.

In order to find the brain activity corresponding to subjective preference, an attempt was made to analyze the effective duration of ACF, τ_e in the alpha-wave range (8-13 Hz) of EEG. First of all, considering the fact that the subjective preference judgement needs at least 2 s to develop a psychological response, the running integration interval (2T) was examined for periods between 1.0 s and 4.0 s. A satisfactory duration 2T in the ACF analyses was found only from the left hemisphere for 2 to 3 s, but not from the right (Ando and Chen, 1996).

In order to analyze the data in more detail for each category Δt_1 and the left and right hemispheres, we show the averaged value of τ_e in the alpha-wave with 11 subjects in Fig. 12. A clear tendency is apparent. Values of τ_e at Δt_1 = 35 ms are significantly longer than those at Δt_1 = 245 ms ($p < 0.01$) only on the left hemisphere, but not on the right. Ratios of τ_e values in the alpha-wave range at Δt_1 = 35 ms and 245 ms, for each subject, are shown in Fig. 13. Remarkably, all of individual data indicate that the ratios in the left hemisphere at the preferred condition of 35 ms are much larger than those in the right hemisphere.

Thus, the results reconfirm that, when the Δt_1 is changed, the left hemisphere is highly activated, and the value of τ_e for the alpha-wave of this hemisphere corresponds well with subjective preference. The alpha-wave has the longest period in the EEG in the awakening stage and may indicate a fullness of “pleasantness” and “comfort”, a preferred condition, which is widely accepted. Thus, a long value of τ_e in the alpha-wave may relate to the long N_2 latency of SVR at the preferred condition discussed above.

3.3.2 EEG in Change of Subsequent Reverberation Time

Now, let us examine values of τ_e in the alpha-wave with changes in the T_{sub}, with 10 subjects, relative to the scale values of subjective preference (Chen and Ando, 1996). The sound source used was music motif B, the same as above. The EEGs from the left- and right-hemisphere were recorded. Values of τ_e of the alpha-wave, for the duration 2T = 2.5 s, were also analyzed here.

First consider the averaged values of τ_e of the alpha-wave, shown in Fig. 14. Clearly, the values of τ_e are much longer at the preferred condition T_{sub} = 1.2 s than those at T_{sub} = 0.2 s in the left hemisphere, while the values of τ_e are longer at

(a) (b)

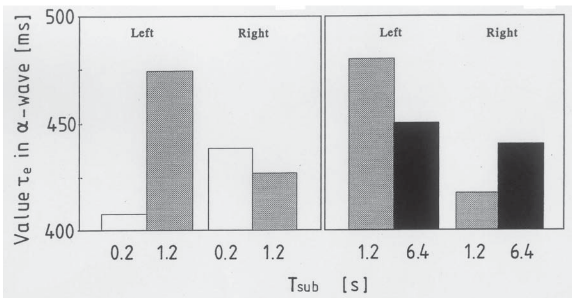

Fig. 14. Averaged value of τ_e in the alpha-brain wave range for the change of T_{sub}: 0.2 s of the less preferred condition and 1.2 s of the preferred condition (10 subjects). Left: left hemisphere; and Right: right hemisphere (Chen and Ando, 1996).

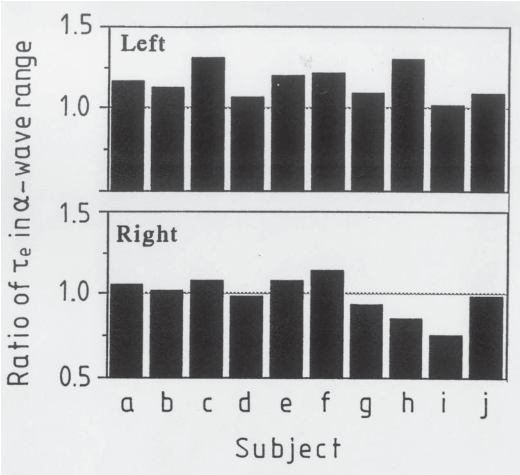

Fig. 15. Ratio of τ_e values in the alpha-brain wave range for the change of T_{sub}: 1.2 s of the preferred condition and 0.2 s of the less preferred condition (10 subjects, a - j). Left: left hemisphere; and Right: right hemisphere (Chen and Ando, 1996).

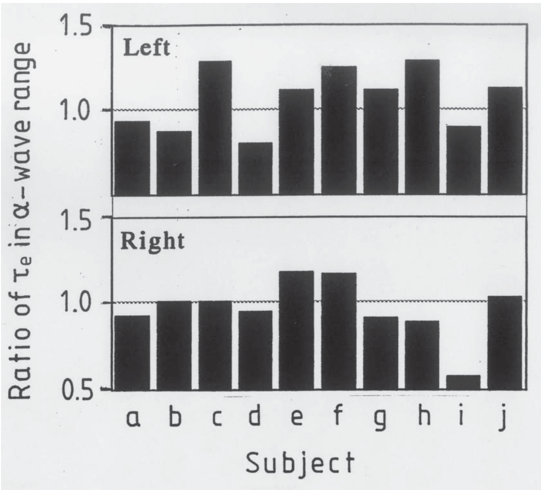

Fig. 16. Ratio of τ_e values in the alpha-brain wave range for the change of T_{sub}: 1.2 s of the preferred condition and 6.4 s of the less preferred condition (10 subjects, a - j). Left: left hemisphere; and Right: right hemisphere (Chen and Ando, 1996).

T_{sub} = 1.2 s than those at T_{sub} = 6.4 s, also in the left hemisphere. However, this is not true for the right hemisphere; rather, the contrary is true.

In order to discuss the matter in more detail, the ratio of values of τ_e for the alpha-wave are shown in Fig. 15 for each subject. All of individual data indicate that the ratios in the left hemisphere are much larger than the ratios in the right hemisphere at T_{sub} = 1.2 s in reference to T_{sub} = 0.2 s (Fig. 15). However, this is not the case for T_{sub} = 1.2 s relative to T_{sub} =6.4 s, indicating large individual differences (Fig. 16).

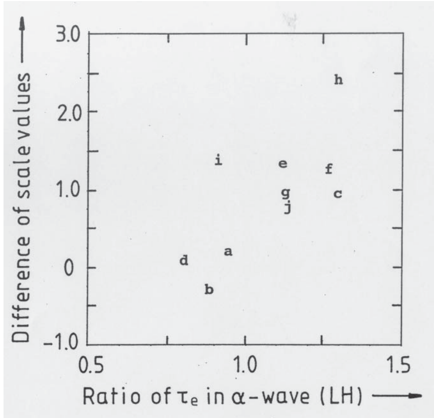

Fig. 17. Relationship between difference of scale values [SV(1.2 s) – SV(6.4 s)] and ratio of τ_e values for alpha-brain waves of the left hemisphere as shown in Fig. 16. These values are obtained with each individual subject, in its change of T_{sub} (1,2 s and 6.4 s) for each of 10 subjects, a – j (Chen and Ando, 1996).

In fact, these individual results correspond well to the scale values of individual subjective preference. Fig. 17 shows the relationship between difference of scale values and ratio of τ_e values. The ratio of values for τ_e of the alpha-wave at 1.2 s and 6.4 s is well correlated to the difference of the scale values of subjective preference for each individual, also reflecting large individual differences, as shown in Fig. 17 ($r = 0.70$, $p < 0.01$).

3.3.3 EEG in Change of IACC

The EEG response to changes in the IACC has been investigated (Sato et al., 2003). More clearly here, with changes to the IACC using music motif B, the right-hemisphere dominance is shown using the analyses of the value of τ_e for the alpha wave. A significant difference is achieved only in the right hemisphere for the pair of sound fields with IACC = 0.95 and 0.30 ($p < 0.01$). The ratio of the values of τ_e in the alpha wave of each subject with change in IACC, [τ_e(IACC=0.3)/τ_e(IACC=0.95)], in the right hemisphere are greater than that in the left hemisphere. Thus, the more preferred condition with smaller IACC is related to the longer value of τ_e for the alpha wave.

Table 1 summarizes the hemisphere dominance obtained by analyses of τ_e for alpha waves, with changes in Δt_1, T_{sub} and the IACC. This finding may suggest that the value of τ_e of alpha waves is an objective index for predicting excellent conditions of the human environment, so far as brain response is concerned.

Photo 1. 122-channel whole-head neuromagnetometer (Neuromag-122™, Neuromag Ltd., Finland)

3.4 Magnetoencephalography (MEG) Corresponding to Subjective Preference in Change of Δt_1

Measurements of responses on MEG were performed in a magnetically shielded room using a 122-channel whole-head neuromagnetometer (Neuromag-122™, Neuromag Ltd., Finland, see Photo 1) (Soeta et al., 2002a). The source signal was the word "piano" with a 0.35-s duration. The minimum value of the moving τ_e, i.e., $(\tau_e)_{min}$, was about 20 ms, which relates closely to the most preferred Δt_1 of sound fields as described by Equation (7) above. In this experiment, the Δt_1 was set at 0, 5, 20, 60, and 100 ms. The direct sound and a single reflection were mixed and the amplitude of the reflection was the same as that of the direct sound ($A_0 = A_1 = 1$). The auditory stimuli were binaurally delivered through a silicon tube and ear piece into the ear canals. The sound-pressure level, which was measured at the end of the tubes, was fixed at 70 dBA.

Seven-23-to 25-year-old male subjects, participated in the experiment. All had normal hearing. They were seated in a dark soundproof room, asked to close their eyes to concentrate

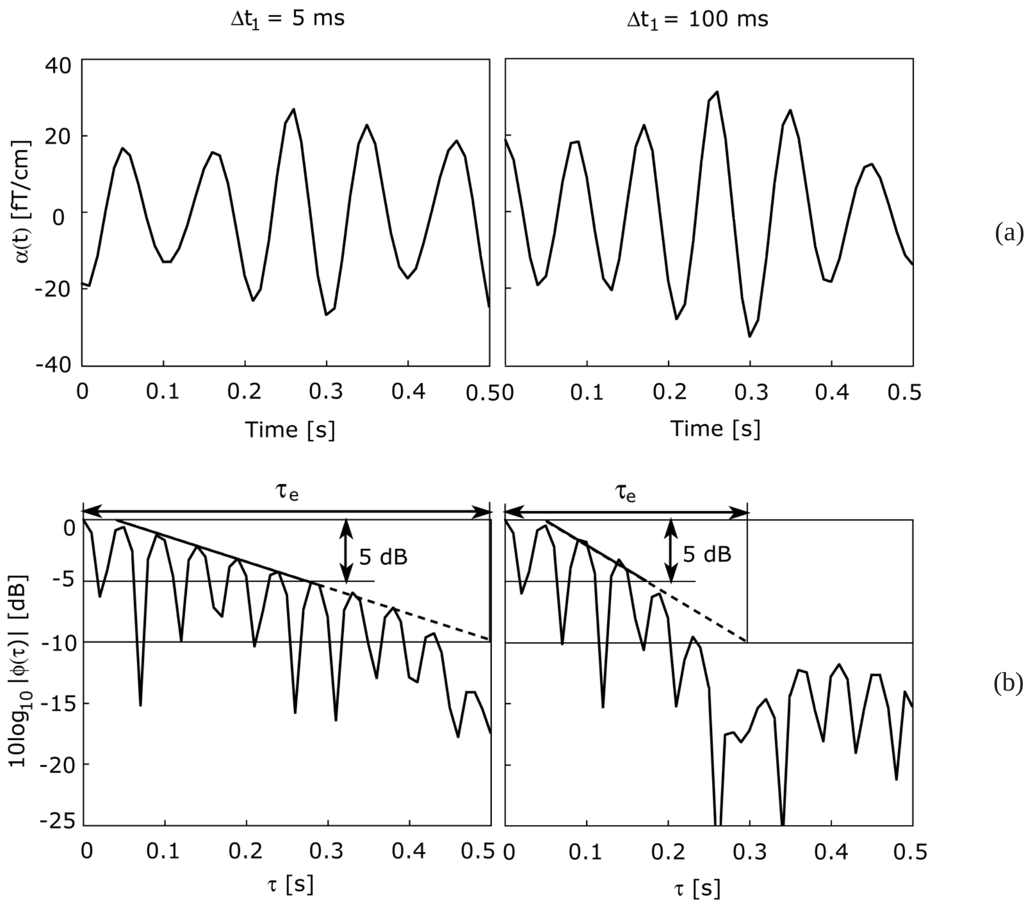

Fig. 18. Examples of the recorded MEG-alpha waves (a) and those of determining the τ_e of ACF (b). MEG records were made for alternative combination (50 times) of a reference stimulus (Δt_1 = 0 ms) and test stimuli with different Δt_1 using sound source of continuous speech signal of 0.35 s at constant 1 s interstimulus interval (Soeta et al., 2002a).

fully on the speech. In accordance with the paired-comparison method, each subject compared ten possible pairs per session, and 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 to allow time for the subjects to respond by pushing one of two buttons.

Measurements of magnetic responses were performed in a magnetically shielded room. Similar to above mentioned EEG measurements, 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, and the MEGs were analyzed. The magnetic data were recorded continuously with a filter of 0.1 - 30.0 Hz and digitized with a sampling rate of 400 Hz. Fig. 18a 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 a N_{1m} response, in the left and right temporal areas. Eight channels that had larger amplitude of N_{1m} response in each hemisphere were selected for the ACF analyses. We analyzed each epoch, which is each response corresponding to one stimulus, for each subject. Fig. 18b show an example

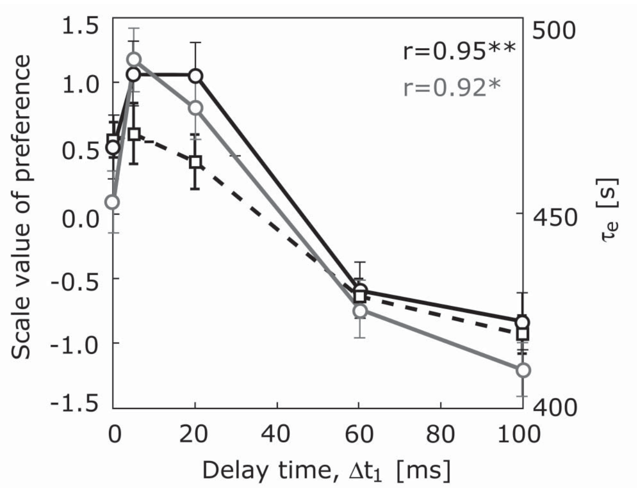

Fig. 19. Relationship between scale values of subjective preference and averaged τ_e values in the alpha-brain waves of MEG over the left and right hemisphere obtained with 8 subjects. Dashed line is the scale value of subjective preference, solid black lines is τ_e values in the alpha-brain waves over the left hemisphere, and solid gray line is τ_e values in the alpha-brain waves over the right hemisphere (Soeta et al., 2002a).

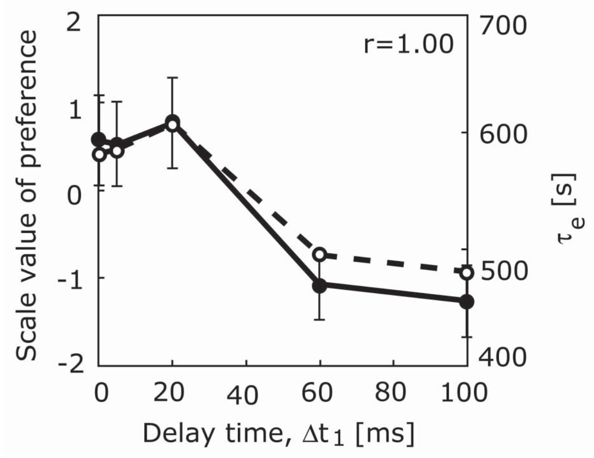

Fig. 20. An example of relationship between scale values of subjective preference and averaged τ_e values in the alpha-brain waves (MEG) over the left hemisphere of a single subject. The correlation coefficient r between them is 1.00. The similar tendencies were achieved for all of 8 subjects tested, r = 0.94 - 1.00 (Soeta et al., 2002a).

of values of τ_e obtained by the straight line for 5 dB from the top of the normalized ACF expressed in logarithm.

Results with eight subjects confirm a linear relationship between the averaged τ_e values of the alpha wave and the averaged scale values of subjective preference. Their correlation coefficients were 0.95 ($p < 0.01$) in the left hemisphere and 0.92 ($p < 0.05$) in the right one as shown in Fig. 19. Since the left-hemisphere dominates Δt_1, reconfirming above-mentioned studies of SVR and EEG, the results of individual level from the left hemisphere are analyzed. Almost direct relationships between the individual scale values of subjective preference and the τ_e values over the left hemisphere of all of eight subjects are found. An example this for a single subject is shown in Fig. 20. It is worth noticing that the correlation coefficient for each subject was achieved more than 0.94 for all of subjects.

The value of 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. However, the amplitude of EEG and MEG did not correspond so well to the scale value of subjective preference. This tendency for a longer τ_e under the preferred condition is much more significant than the results of previous studies on EEG alpha waves (Ando and Chen, 1996; Chen and Ando, 1996; Chen et al., 1997; Sato et al., 2003).

4. SUMMARY OF FINDINGS

Recordings over left and right hemispheres of ABR, SVR, EEG and MEG have revealed following evidences.

4.1 ABR Corresponding to ACF and IACF

(1) Comparing results between Fig. 5a and Fig. 5b, the relative behavior of wave IV_l is similar to the sound energy $\Phi_{rr}(0)$ measured at the right-ear entrance. Also, the relative behavior of wave IV_r is similar to $\Phi_{ll}(0)$ at the left-ear entrance;
(2) The relative behaviors of wave V observed at inferior colliculus correspond well to the IACC (Fig. 5 and Fig. 6).

4.2 SVR Corresponding to Subjective Preference

(1) The left and right amplitudes of the early SVR, $A(P_1 - N_1)$ indicate that the left and right hemispheric dominance are due to the temporal factor (Δt_1) and spatial factors (LL and IACC), respectively, as indicated in Table 1. It is worth noticing that the SL or LL is classified as a temporal-monaural factor in from a physical viewpoint. However, the results of SVR indicate that SL is right hemisphere dominant. Thus, SL or LL is classified as a spatial factor, which is expressed by a geometric average value of the sound energies arriving at the two ears;
(2) Both left and right latencies of N_2 correspond well to the IACC, and thus the scale values of subjective preference as a primitive response.

4.3 EEG Corresponding to Subjective Preference

(1) Results of EEG for the cerebral hemispheric specialization of the temporal factors, i.e., Δt_1 and T_{sub} indicate left hemisphere dominance, and the IACC response indicates right hemisphere dominance. Thus, a high degree of independence between the left and right hemispheric factors is achieved;
(2) The scale value of subjective preference is well described in relation to the value of τ_e extracted from ACF of the alpha-wave over the left hemisphere and the right hemisphere according to the change of temporal and spatial factors of sound fields, respectively.

4.4 MEG Corresponding to Subjective Preference

(1) Amplitudes of MEG recorded when Δt_1 was changed reconfirms the left hemisphere specialization;
(2) The scale values of individual subjective preference relate most directly to the value of τ_e extracted from the ACF of the alpha-wave of MEG; It is worth noticing that the amplitudes of the alpha-wave in MEG do not correspond well to the scale value of subjective preference.

In addition to above mentioned temporal activities both on the left and right hemispheres, spatial activities on the brain were analyzed by the cross-correlation function of alpha waves of EEG and MEG. The results show that a large area of the brain is activated, when the preferred sound fields are presented (Sato et al, 2003; Soeta et al., 2003).

5. APPLICATIONS

It is quite possible that this kind of concept may be applied not only for acoustic design of concert halls and opera house, but also for environmental noise measurement, its evaluation (Ando, 2001; Ando and Pompoli, 2002), and speech intelligibility (Ando et al., 1999) in a sound field. Also, both spatial and temporal factors are explicitly considered in a general theory of physical environment design including vision based on the brain activities. Further idea of temporal design and the applications in the wide range of fields are being published in this journal (http://www.jtdweb.org/).

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APPENDIX A PHYSICAL SYSTEM OF HUMAN EARS

This appendix describes the sensitivity of the human ear to a sound source that is formed primarily by the physical system consisting of the external canal, eardrum and bone chain with oval window.

A.1 Physical Systems of Human Ears

A.1.1 Head, Pinna and External Auditory Canal

The ears perceive the sound signal given by a time sequence. The ears also perceive the three-dimensional space, mainly because the HRTF $H_{l,r}(r|r_0, \omega)$ between a source point and the two ear entrances have directional qualities from the shapes of the head and the pinna system. The directional information is contained in such HRTFs, including the interaural time difference.

Figure A1 shows examples of the amplitude of the HRTF $H(\xi, \eta, \omega)$ as parameters of the angle of incidence ξ (η = 0°). These were measured by the single-pulse method at the far field condition (Mehrgardt and Mellert, 1977). The angle ξ = 0° corresponds to the frontal direction and ξ = 90° to the lateral direction towards the side of the ear being examined. Remarkably in the median plane, no factors extracted from the HRTF are figured out to explain the sound localization, however, cues in term of the temporal factors, τ_1, ϕ_1 and τ_e extracted from ACF derived by the head-related impulse response, $h_{l,r}(r|r_0, t)$, are significantly differ (Sato et al, 2001).

Since the diameter of the external canal is small enough compared with the wavelength (below 8 kHz), the transfer function of E(ω) is independent of the directions in which sound is incident on the human head for the audio frequency range:

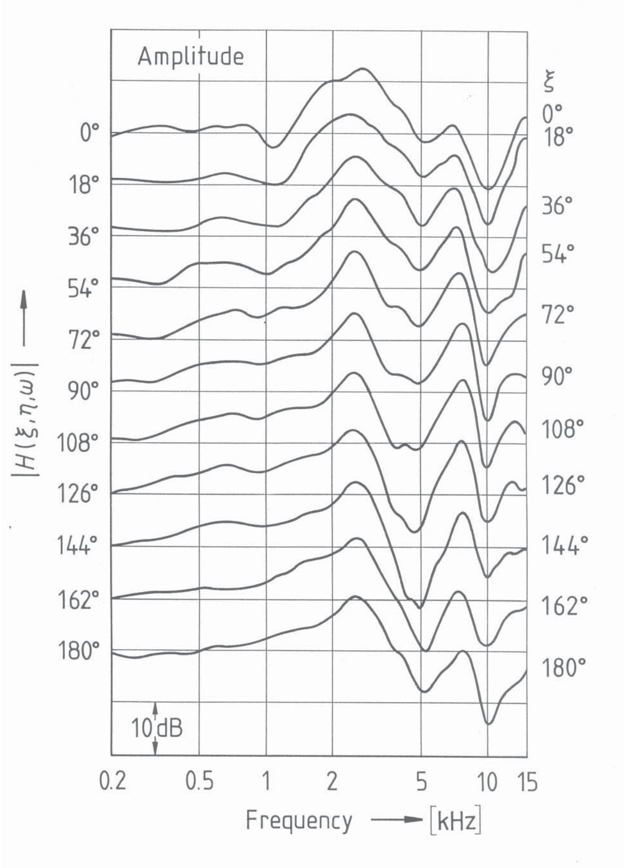


Fig. A.1. Amplitude of the HRTF from a free field to the ear-canal entrance as a parameter of the horizontal angle ξ (Mehrgardt and Mellert, 1977).

$$E_{l,r}(\xi, \eta, \omega) \approx E_{l,r}(\omega) \approx E(\omega) \qquad \text{(A-1)}$$

Therefore, interaction between the sound field in the external canal and that of the outside, including the pinna, is insignificant. The transfer function from the free field to the eardrum can be obtained by multiplying together the following two functions;
(1) the sound field from the sound source in the free field to the ear-canal entrances, $H_{l,r}(\xi, \eta, \omega)$, and
(2) the sound field from the entrance to the eardrum, E(ω).
Measured absolute values of E(ω) are shown in Fig. A.2, where the variations in the curves obtained by different investigations are caused mainly by the different definitions of the ear-canal entrance point. A typical example of transfer function from a sound source in front of the listener to the eardrum is shown in Fig. A.3. This corresponds to direct sound when the listener is facing the performer. The transfer functions obtained by these three reports (Wiener and Ross, 1946; Shaw, 1974; Mehrgardt and Mellert, 1977) are not significantly different for frequencies up to 10 kHz.

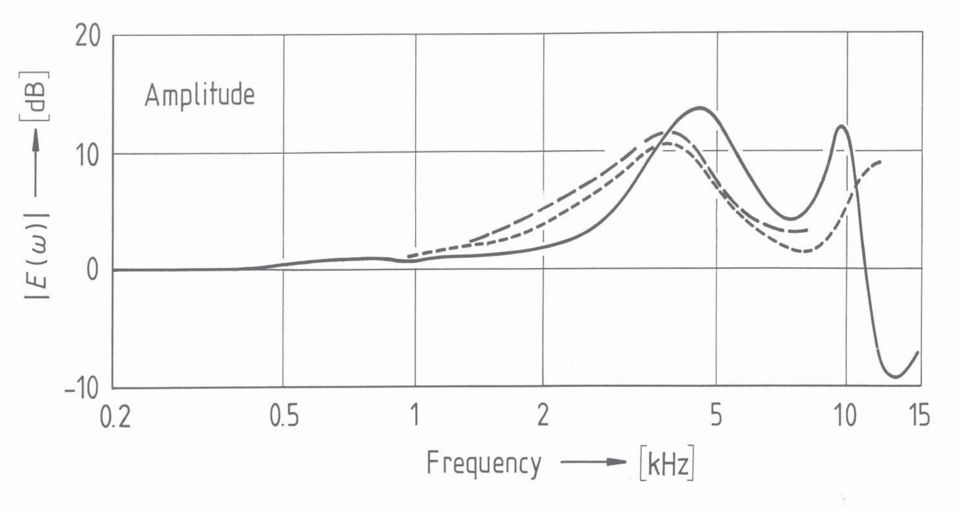


Fig. A.2. Transfer functions of the ear canal. (------) : From Wiener and Ross (1946); (......) : from Shaw (1974); (____): from Mehrgardt and Mellert (1977).

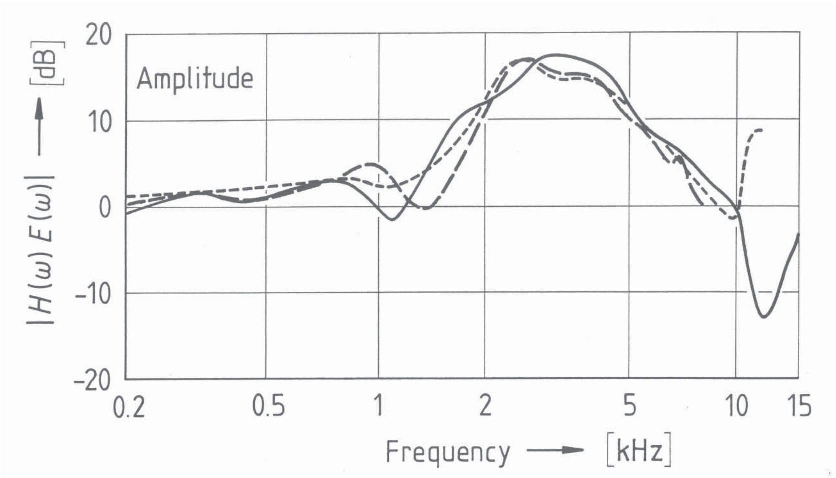


Fig. A.3. Transfer functions to the eardrum from a sound source in front of the listener. (------) : From Wiener and Ross (1946); (......) : from Shaw (1974); (____): from Mehrgardt and Mellert (1977).

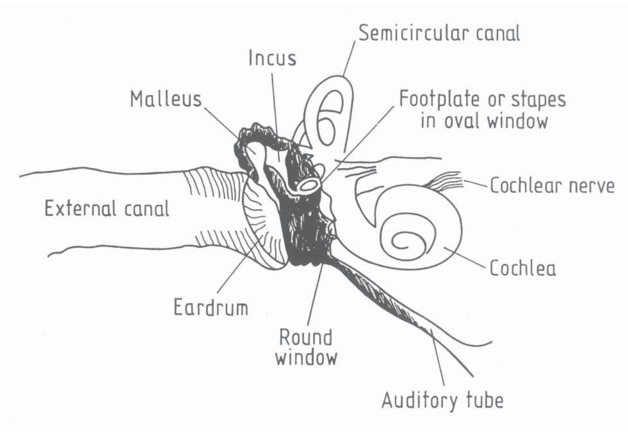


Fig. A.4. Schematic illustration of human ear (modified from Dorland, 1947).

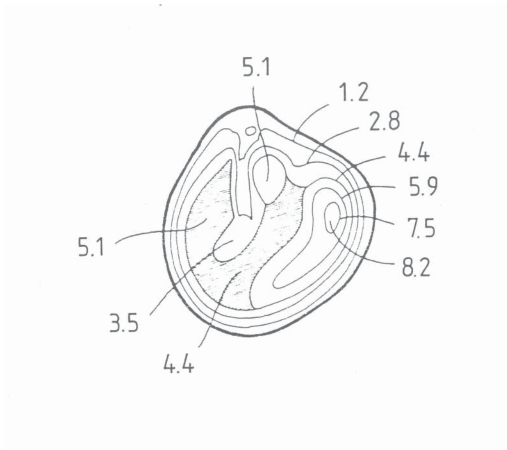


Fig. A.5. Contour lines of equal amplitude of human eardrum vibration at 525 Hz (121 dB SPL). Each value should be multiplied by 10^{-5} cm (Tonndorf and Khanna, 1972).

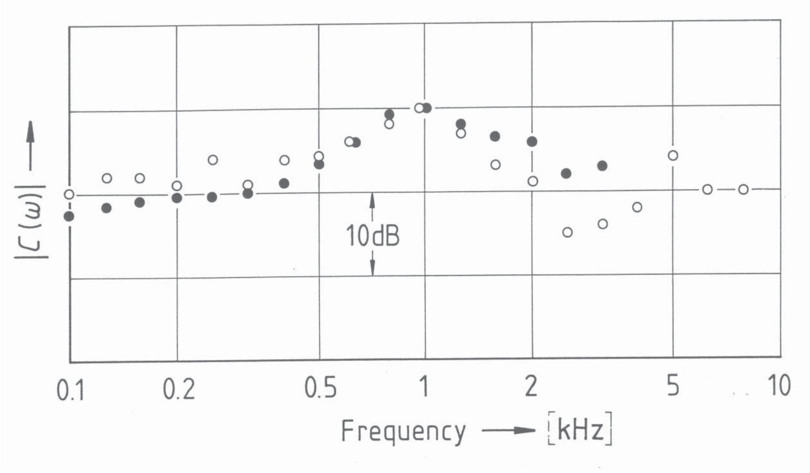


Fig. A.6. Transfer function (relative amplitude) of human middle ear between the sound pressure at the eardrum and the apparent pressure on the cochlea. Full circle: Average value measured (modified from Onchi, 1961); Empty circle: Measured value (Rubinstein, 1966).

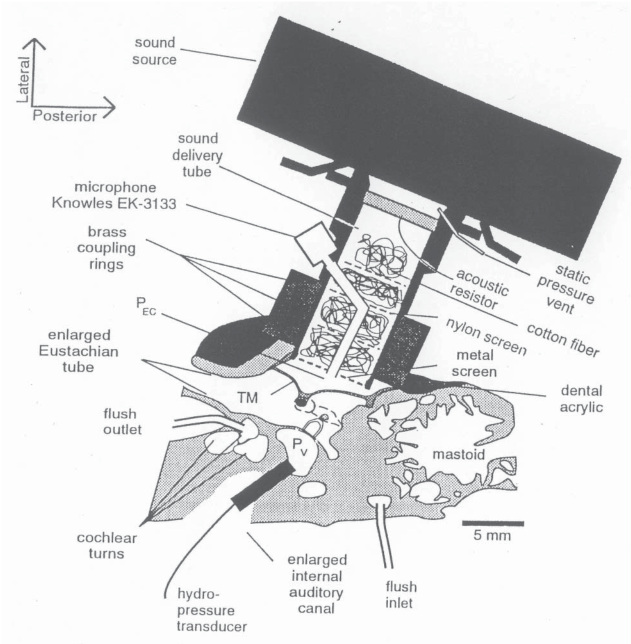


Fig. A.7. Measurement system of middle ear transfer function. To measure the inner-ear pressure, a hydropressure transducer was placed in the vestibule facing the stapes. In order to ensure that the cochlea remains fluid filled during the measurement, an inlet flush tube was cemented into the superior semi-circular canal and an outlet flush tube was cemented into the apical turn of the cochlea (Puria et al., 1993).

A.1.2 Eardrum and Bone Chain

Behind the eardrum are the tympanic cavities containing the three auditory ossicles, the malleus, incus, and stapes. This area is called the middle ear (Fig. A.4). The sound pressure striking the eardrum is transduced into vibration. The middle ear ossicles transmit the vibration to the cochlea. Békésy (1960) first measured the vibration pattern of the human eardrum by making a point-by-point examination with an electric capacitive probe. Later, Tonndorf and Khanna (1972) measured the vibration pattern by time-averaged holography, which allows finer vibration patterns on the eardrum to be perceived, as shown in Fig. A.5. It is interesting that the outline of the malleus is visible in the pattern at the value of 3.5. The vibration on the malleus is transmitted to the incus and the stapes. The transfer function C(ω) of the human middle ear between the sound pressure at the eardrum and the apparent sound pressure on the cochlea is plotted in Fig. A.6. Onchi (1961) and Rubinstein (1966) obtained data from cadavers, and the author has rearranged values, so that the maxima at 1 kHz are adjusted to the same value. Later, Puria et al., (1993) made measurements by a system that included a hydropressure transducer used in the vestibule as shown in Fig. A.7. The hydropressure transducer and the microphone with identical sound pressure stimuli in air produced estimates of pressure within 0.5 dB for the range of 50 Hz - 11 kHz. The results at the sound pressure levels of 106, 112 and 118 dB indicating similar values are shown in Fig. A.8. These results agree well with the data shown in Fig. A.6, so far as relative behavior is concerned. The transfer function measured at 124 dB showed some signs of nonlinearity, but below about 118 dB were consistent with a linear system. The magnitude of the middle-ear pressure gain is about 20 dB in the frequency range 500 Hz to 2 kHz.

For the usual sound field, the transfer function between a sound source located in front of the listener and the cochlea may be represented by

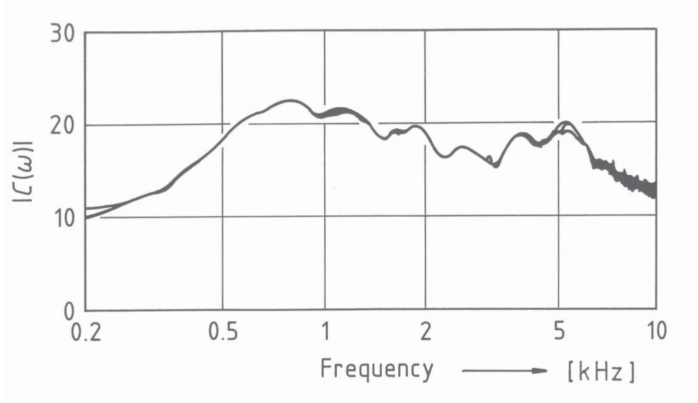


Fig. A.8. Transfer function of human middle ear between the sound pressure at the eardrum and the inner-ear pressure (Puria et al., 1993). The global behavior is surprisingly similar to that of Fig. A.6.

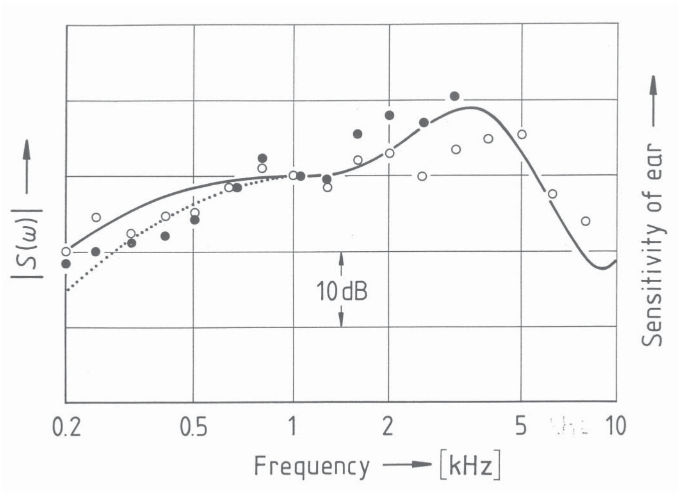


Fig. A.9. Sensitivity of human ear to a sound source in front of listeners. (____): Normal hearing threshold (ISO recommendation); (......): Reexamined in the low frequency range (Berger, 1981); Full and empty circles: Transformation characteristics between the sound source and the oval window, $S(\omega) = H(\omega)E(\omega)C(\omega)$; Full circles: Data obtained from measured values $C(\omega)$ by Onchi (1961), and empty circles: from Rubinstein (1966), which are combined with the transfer function $H(\omega)E(\omega)$ measured by Mehrgardt and Mellert (1977).

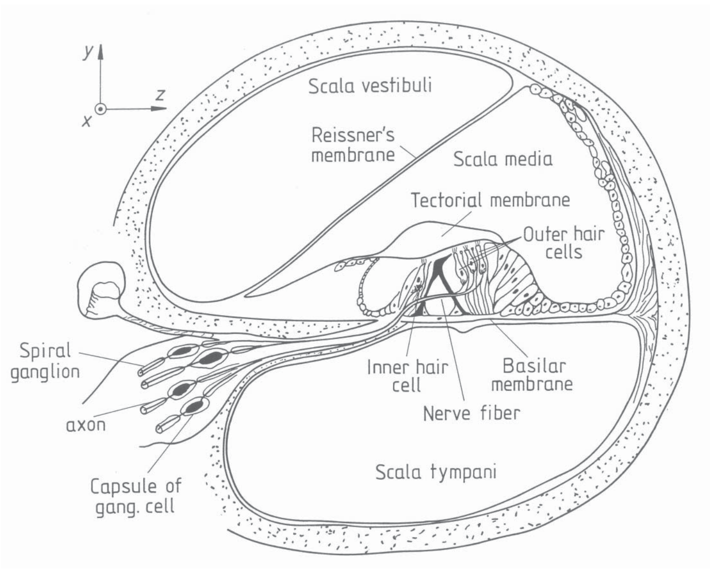


Fig. A.10. Cross section through the cochlea showing the fluid filled canals and the basilar membrane supporting hair cells (modified from Rasmussen, 1943).

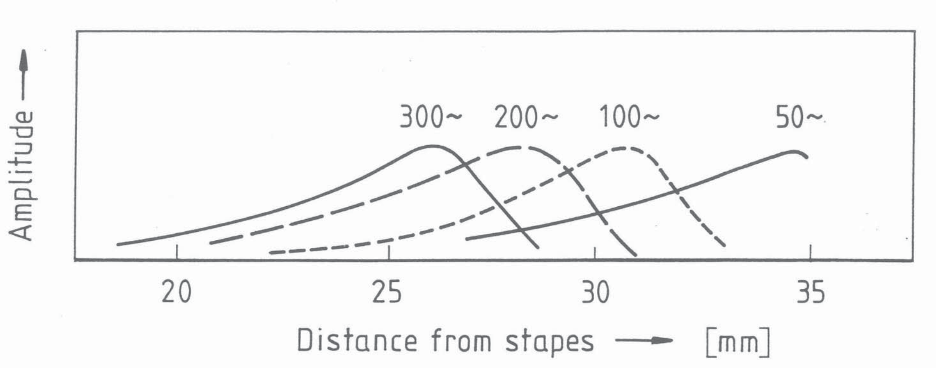


Fig. A.11. Envelope of the traveling wave (Békésy, 1960).

$$S(\omega) = H(0, 0, \omega)E(\omega)C(\omega) \quad \text{(A.2)}$$

The values are plotted in Fig. A.9 with data from Onchi (1961) and Rubinstein (1966). The pattern of the transfer function agrees with the ear sensitivity for people with normal hearing ability, so that the ear sensitivity may be characterized primarily by the transfer function from the free field to the cochlea (Zwislocki, 1976). Better agreement may be obtained with the values reexamined in the low-frequency range (Berger, 1981).

A.2 Cochlea

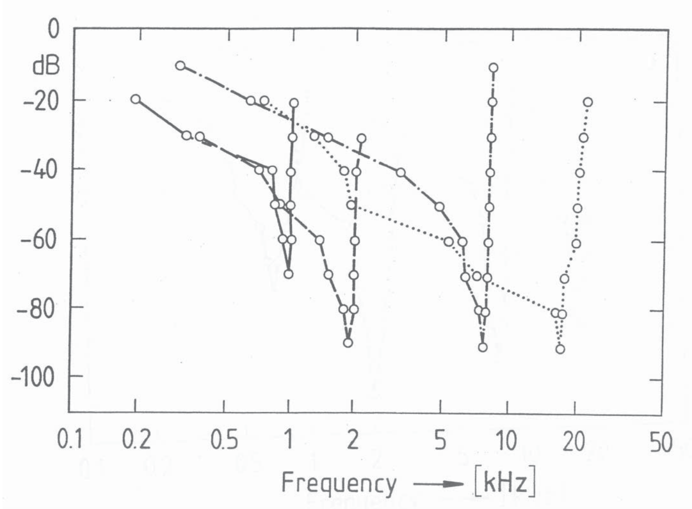
The stapes is the last bone of the three auditory ossicles, and is the smallest bone of the human body. It is connected with the oval window, and drives the fluid in the cochlea, producing a traveling wave along the basilar membrane. The cochlea contains the sensory receptor organ on the basilar membrane, which transforms the fluid vibration into the neural code, Fig. A.10. The basilar membrane is so flexible that each section can move independently of the neighboring section. The traveling waves on the basilar membrane observed by Békésy (1960), Fig. A.11 is consistent with this representation.

2.3 Nervous System

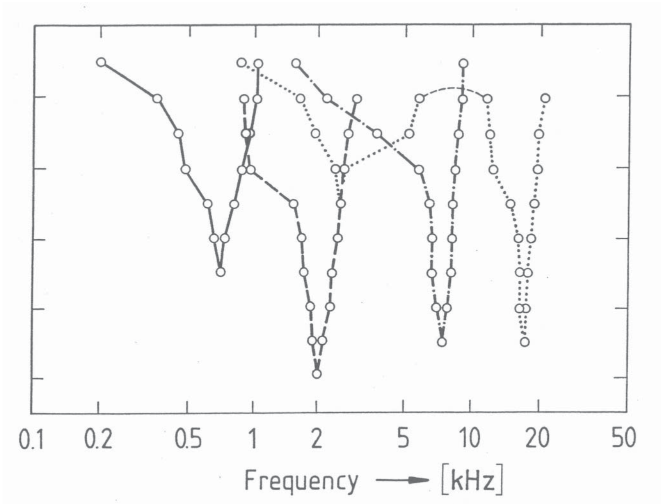
The nervous system is one of the most important parts in the whole acoustic system. Obviously, there are some deep connections between sound signals, responses of the auditory system and brain, and subjective attributes, as covered in this system.

The mechanical information in the traveling waves on the basilar membrane is transduced into biological information. The transducers, consisting of about 15000 receptors on the basilar membrane, are specialized nerve cells called hair cells. The action potentials from the hair cells are conducted and transmitted to a higher level in the auditory-path way. Katsuki and his group (1958) first systematically demonstrated the frequency response curve, called the "tuning curve" of a single fiber, in auditory pathway. The results of the threshold response in the potential activity of the cochlear nerve of a cat are shown in Fig. A.12a, and of the trapezoid body in Fig. A.12b. The important phenomenon is the so-called sharpening effect. The tuning curve becomes sharper than the resonance curve on the basilar membrane. This tendency becomes more distinct at higher levels and the slope reaches the order of 1000 dB/Oct. Békésy (1967) explained this as a result of a lateral inhibition action of neural networks as the place activity. Interactions between neighboring neurons are responsible at least partially for the sharpening. Therefore, responses of a single pure tone ω tend to approach a limited region in the auditory pathway x'. Accordingly, the input power density spectrum of the cochlea $I(\omega)$ can be roughly mapped at the nerve position x', so that the spectrum can be written as $I(x')$. In addition, such a sharpening effects might occur in the temporal activity. In fact as mentioned in the introductory chapter, pooled interspike interval distributions resemble the short time or the running ACF for the low-frequency component. And, pooled interval distributions for sound stimuli consisting of the high-frequency component resemble the envelope to running ACF (Cariani and Delgutte, 1996).

In addition to the cochlea nuclei, there are the superior olivary complex, the lateral lemniscus nuclei, the inferior colliculus and the medial geniculate body. Neural signals as investigated by use of ABR are processed at every relay station. Since several interaural cross connections are known to exist as physiological structures (ex. Pickles, 1982), it has been achieved that there exists an IACC mechanism at the inferior colliculus as discussed in Section 2.4. In Sections 3.2 through 3.4, results of some experiments with records of electro-and



(a)



(b)

Fig. A.12. Frequency response functions of single fibers as threshold responses in the potential activity of a cat's auditory system. Each line indicates the response of different single fibers. Curves of the threshold correspond well to sensation (Katsuki et al., 1958). (a) Cochlea nerve, (b) Trapezoid body.

magnetro-responses from the auditory pathways and the left and right cerebral hemispheres are described.

APPENDIX B SCALE VALUE OF INDIVIDUAL PREFERENCE BASED ON THE PAIRED-COMPARISON TESTS

The minimum unit of audience is the single individual. If the environment satisfies each individual, then the whole audience is satisfied. But, the opposite is not true. Even if the condition of preference is satisfied as a general standard, in the initial design, some listeners may not be as satisfied. In this chapter, first of all, a method is discussed for determining individual subjective preference for sound fields. Then, results of individual differences are presented. As an example of an application, we now describe a seat selection system that enhances individual preference

.

B.1 Scale Value Obtained by the Paired-Comparison Tests (Thurstone, 1927)

Considering the fact that person, including children and aged people, are quite diverse, a method for subjective judgments should be as simple as possible. For this purpose, the paired-comparison method has been selected. Another method, for example, the method of magnitude estimate is too difficult for most people, except for the skilled subjects in laboratory experiments. First of all, the fundamental idea of obtaining the scale value is mentioned here. The paired-comparison method usually needs a number of judgments for a single pair.

The probability that a sound field *B* is preferred to another sound field *A* is expressed by

$$P(B > A) = \frac{1}{\sigma_d\sqrt{2\pi}}\int_0^\infty \exp(\frac{(X_d - <X_d>)^2}{2\sigma_d})\, dX_d$$

$$= \frac{1}{\sqrt{2\pi}}\int_{Z_{ab}}^{\infty} \exp(\frac{y^2}{2})dy \qquad \text{(B.1)}$$

where

$$Z_{ab} = -\frac{<X_d>}{\sigma_d} \qquad \text{(B.2)}$$

$<X_d>$ is the average scale value between sound fields *A* and *B*, $X_d = X_b - X_a$, if σ_d is being used as the unit for the scale value: $\sigma_d = 1$.

Thus,

$$P(B > A) = erfc[Z_{ab}] \qquad \text{(B.3)}$$

$$Z_{ab} = erfc^{-1}[P(B > A)] \qquad \text{(B.4)}$$

B.2 A Simple Method for Obtaining Individual Preference

The first order approximation of the Taylor series of Equation (B.4) is given by

$$Z_{ab} = \sqrt{2\pi}\ (P(B > A)–1/2) \qquad \text{(B.5)}$$

The linear range can be obtained for

$$0.05 \le P(B > A) \le 0.95.$$

However, from a single observation datum for a set of sound fields, an approximate method is described for obtaining the scale value of subjective preference. The method is based on the law of comparative judgment using the linear range of normal distribution between the probability and the scale value.

Let us now consider the number of sound fields, given by F (i, j = 1, 2,..., F), and suppose a single response of each pair, for simplicity. Then the probability P(B > A) in Equation (B.5) is replaced by (Ando and Singh, 1996)

$$P(i > j) = \frac{1}{F}\sum_{i=1}^{F} Y_i \qquad \text{(B.6)}$$

where Y_i = 1 responds to a preference of i over j, $Y_i = Y_j$ = 0.5 ($i = j$), while Y_i = 0 corresponds a preference of j over i. In order to improve the precision of the probability $P(i > j)$, a certain minimum number of sound fields within the linear range are needed, to keep the accuracy high when using Equation (B.6). This is performed by a preliminary investigation, avoiding any extreme sound field outside the linear range. In this a manner, the scale value $S_i = Z_{ij}$ (i = 1, 2, ..., F) may be obtained approximately, when Z_{ij} with $P(j > i)$ is obtained by Equation (B.5).

Next, let us consider an error in a single observation. The poorness of fit for the model is defined by

$$\lambda = \frac{\sum_{(i,j)} \left|S_i - S_j\right|_{Poor}}{\sum_{(i,j)} \left|S_i - S_j\right|}, \qquad 0 \le \lambda \le 1 \qquad \text{(B.7)}$$

where

$$|S_i - S_j|_{Poor} = S_j - S_i, \qquad \text{if } Y_i = 0$$
$$= 0, \qquad \text{if } Y_i = 1 \qquad \text{(B.8)}$$

Thus, in spite of j is being preferred over i (Y_i = 0), it is possible that $S_j - S_i < 0$, and the amount $|S_i - S_j|_{Poor}$ is added as in Equation (B.7). When i is preferred over j (Y_i = 1), it is natural that $S_i - S_j > 0$, and the amount is not added to the numerator. The value of corresponds to the average error of the scale value. This should be small enough, say, less than 10 %.

Another observation is that, when the poorness number is K, according to the condition expressed by (B.8), then the percentage of violation d is defined by

$$d = \frac{2K}{N(N-1)} \times 100 \qquad \text{(B.9)}$$

B.3 Examples of Individual Preference

Table B.1 indicates typical examples of preference judgments with a single subject. The number of simulated sound fields was F = 12, with variation of both the LL and the IACC. The value T_i is the aggregated preference scores of each sound field. For the scale values listed in Table B.1, the number of violations K = 6 thus, d = 9.1 %, and λ = 0.04.

The results of scale values obtained as a function of the LL and as a parameter of the IACC, for a single subject with music motif A, are shown in Fig. B.1. Almost parallel curves of values of IACC are observed. This reveals that both the LL and the IACC independently influence the subjective preference judgments. Hence, the scale values of preference may be described by each of the two factors, similar to the global preference with a number of subjects. The most preferred LL is always found to be close to 77 dBA for any

Table B.1. Example of scale values, S_i, estimated by aggregating the preference scores (0 or 1). The paired-comparison tests were conducted by changing both LL and IACC with music motif A (subject OS).

Sound field LL [dB]	IACC		1	2	3	4	5	6	7	8	9	10	11	12	T_i	P(i>j)	S_i
83	0.98	1	.5	0	0	0	0	0	1	0	0	0	0	0	1.5	0.13	-0.94
83	0.72	2	1	.5	0	0	0	0	0	0	0	1	0	0	2.5	0.21	-0.73
83	0.39	3	1	1	.5	1	0	0	0	0	0	1	0	0	4.5	0.38	-0.31
80	0.98	4	1	1	0	.5	0	0	1	0	0	1	0	0	4.5	0.38	-0.31
80	0.72	5	1	1	1	1	.5	0	1	0	0	1	1	1	8.5	0.71	0.52
80	0.39	6	1	1	1	1	1	.5	1	0	1	1	1	1	10.5	0.88	0.94
77	0.98	7	0	1	1	0	0	0	.5	1	0	1	1	0	5.5	0.49	-0.10
77	0.72	8	1	1	1	1	1	1	0	.5	0	1	1	1	9.5	0.79	0.73
77	0.39	9	1	1	1	1	1	0	1	1	.5	1	1	1	10.5	0.88	0.94
74	0.98	10	1	0	0	0	0	0	0	0	0	.5	0	0	1.5	0.13	-0.94
74	0.72	11	1	1	1	1	0	0	0	0	0	1	.5	0	5.5	0.49	-0.10
74	0.39	12	1	1	1	1	0	0	1	0	0	1	1	.5	7.5	0.63	0.31

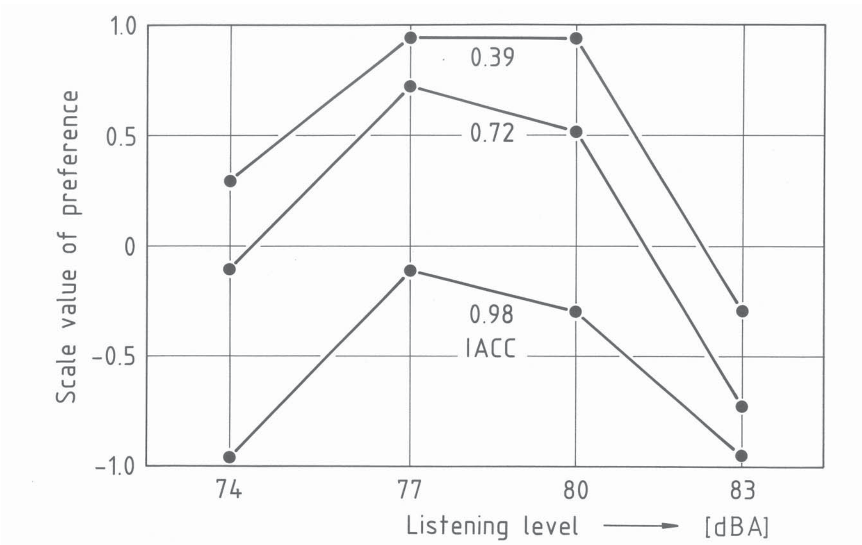


Fig. B.1. Scale values of preference for each sound field obtained by the paired-comparison test as a function of LL and as a parameter of IACC (subject OS, music motif A: Royal Pavane by Gibbons).

value of the IACC. Therefore, no interactive behavior may be found from the parallel curves due to changes in the IACC, and the similar curve shapes relative to the LL, in spite of the same right hemispheric dominance. For instance, smaller values of the IACC are always preferred, regardless of the LL. Thus, the scale values for the two factors are determined, and are superposed. This kind of independence of the two factors was verified for all other 15 subjects who participated.

The same is true for other combinations of orthogonal factors of sound fields (Ando, 1985; 1998). Typically, this independent behavior may be found for other two factors, both associated with left hemisphere: T_{sub} and Δt_1.