콘서트홀 음향

- 음악과 홀을 융합시키는 물리학, 생리학, 심리학 -

안도 요이찌
고오베 대학 공학부

CONCERT HALL ACOUSTICS

- Physics, Physiology and Psychology fusing Music and Hall -

Yoichi Ando
Faculty of Engineering, Kobe University, Rokkodai, Nada, Kobe 657 Japan

Abstract

The theory of subjective preference with temporal and spatial factors which include sound signals arriving at both ears is described. Then, auditory evoked potentials which may relate to a primitive subjective response namely subjective preference are discussed. According to such fundamental phenomena, a workable model of human auditory-brain system is proposed. For example, important subjective attributes, such as loudness, coloration, threshold of perception of a reflection and echo disturbance as well as subjective preference in relation to the initial time delay gap between the direct sound and the first reflection, and the subsequent reverberation time are well described by the autocorrelation function of source signals. Speech clarity, subjective diffuseness as well as subjective preference are related to the magnitude of interaural crosscorrelation function (IACC). Even the caktail party effects may be explained by spatialization of human brain, i.e., independence of temporal and spatial factors.

Physical Factors Including Sound Signals at Ears

First of all, physical factors included in sound signals at both ears are described by means of mathematical formulation. Fig. 1 shows for simplicity, a sound source $p(t)$ is located on the stage and a listener is seated at a position in a concert hall. The impulse response for the reflection property of walls is expressed by $w(t)$, and two head-related impulse responses are given by $h_L(t)$ and $h_R(t)$ for the left and right ears, respectively. Then, the sound pressure at both ears may be given by

$$f_{L,R}(t) = \sum_n p(t) * A_n w_n(t - \Delta t_n) * h_{nL,R}(t) \quad (1)$$

A_n : Attenuation by the distance

$w_n(t)$: $W_n(\omega)$ [Fourier transform]

$$W_n(\omega) = \prod_i W_{n,i}(\omega) \quad (2)$$

i : Number of times of the reflection

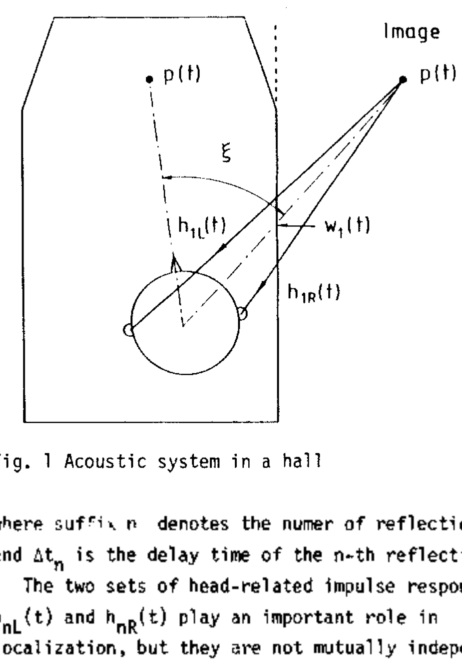

Fig. 1 Acoustic system in a hall

where suffix n denotes the numer of reflections and Δt_n is the delay time of the n-th reflection.

The two sets of head-related impulse response $h_{nL}(t)$ and $h_{nR}(t)$ play an important role in localization, but they are not mutually independent. Thus, in order to represent the interdependence between these impulse responses, we introduce a single factor, the interaural crosscorrelation (IACC).

The source signal $p(t)$ is described by its autocorrelation function which corresponds to the power spectrum. Examples of measured ACF of music pieces of 35 s duration; Royal Pavane by Gibbons (Motif A) and Sinfornietta by Arnold (Motif B) are shown in Fig. 2. The effective duration is defined by the ten percentile delay, τ_e. The value of Motif A is about 130 ms and that of Motif B is about 40 ms.

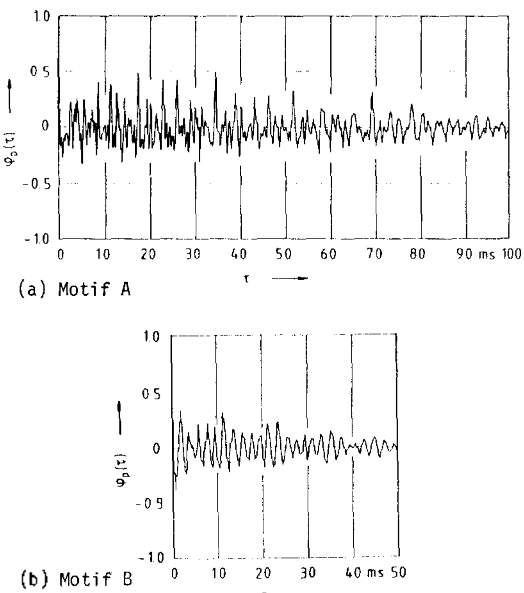

Fig. 2 Examples of measured ACF, the effective duration of ACF differs greatly the tempo of music.

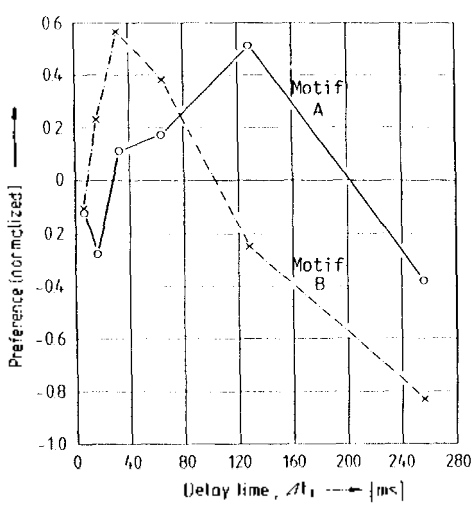

Fig. 3 Preference scores as a function of delay time of the single reflection.

Fig. 3 shows results of subjective preference judgments as a function of the delay time for Motif A and Motif B. For motif A, the most preferred delay time may be found around 130 ms which corresponds to the effective duration of ACF. For motif B, the most preferred delay time is found around 40 ms, this corresponds also the effective duration of ACF of source signal.

Subjective Preference of Sound Field Simulated

Let us now discuss sound fields with early reflections and the subsequent reverberation time simulated for concert halls.

Independent physical factors included in Eq. (1) may be reduced into following four:

(1) Level of listening;
(2) delay time of early reflections;
(3) subsequent reverberation time;
(4) IACC.

The IACC was controlled by adjusting the direction of reflections to the listener.

After examination of independence of four physical factors on subjective preference judgment, the scale value obtained by the law of comparative judgment may be expressed by each factor as shown in Fig. 4.

Different symbolds indicate values obtained by different test series with different program sources, in which abcissa is each physical factor normalized by its most preferred condition.

Theory of Subjective Preference

Since the four physical factors independently influence the subjective preference in the range tested, the scale value of preference may be expressed by

$$S = S_1 + S_2 + S_3 + S_4 \qquad (3)$$

As far as the subjective preference for sound field is concerned, it is interesting that the scale value may be approximated in terms of 3/2 power of the normalized factors as

$$S \approx -\sum_{m=1}^{4} \alpha_m |x_m|^{3/2} \qquad (4)$$

where $x_1 = 20\log P - 20\log[P]_p$; $A = (\Sigma A_n^2)^{1/2}$

$x_2 = \log(\Delta t_1/[\Delta t_1]_p)$; $[\Delta t_1]_p \approx (1-\log A)\tau_e$

$x_3 = \log(T_{sub}/[T_{sub}]_p)$; $[T_{sub}]_p \approx 23\tau_e$

(temporal and monaural factors)

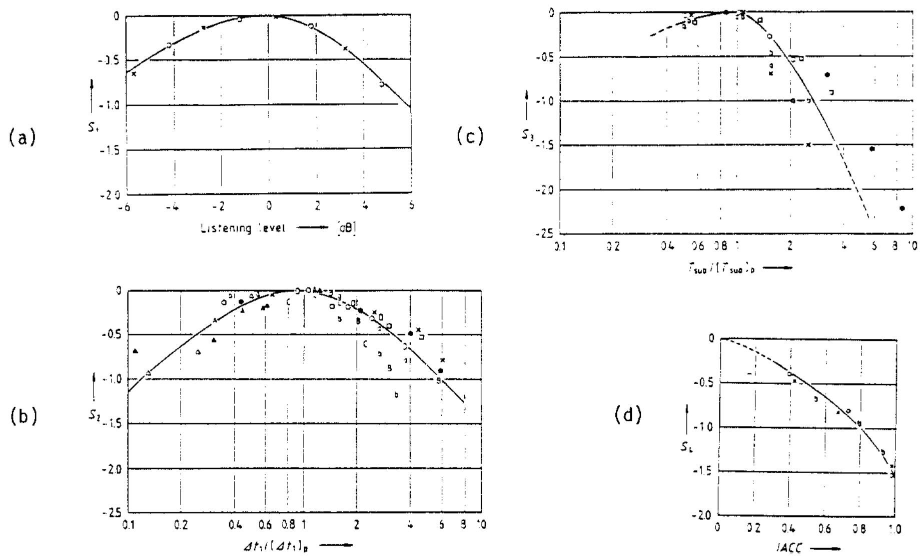

Fig. 4 Scale values of preference as a function of listening level normalized by the most preferred level (a), initial time delay gap between the direct sound and the first reflection (b), subsequent reverberation time (c) and IACC (d).

x_4 = IACC
(spatial and binaural factor)

It is remarkable that for temporal and monaural factors, the normalized factors are expressed in the logarithm, but for the spatial and binaural factor is expressed by its real value, IACC. Therefore, among four factors the IACC may have the strongest contribution to subjective preference.

Example of Calculating Scale Value of Preference

After obtaining the physical properties of a proposed concert hall with its plan and cross section, the scale value at each seat may be calculated. Fig. 5 shows calculated results of the total scale value for two existing concert halls, an auditorium at Kobe University and the Symphony Hall in Boston. If the side walls on the stage are arrenged as shown in left sides of this figure, then total scale values are much improved, particularly in the seating area close to the stage.

Since the original shape of the Boston Hall and its stage enclosure were well designed, the degree of improvement is rather small.

It is worth noticing that reflection from ceiling and back wall of the stage are more important for performance of musician than listener.

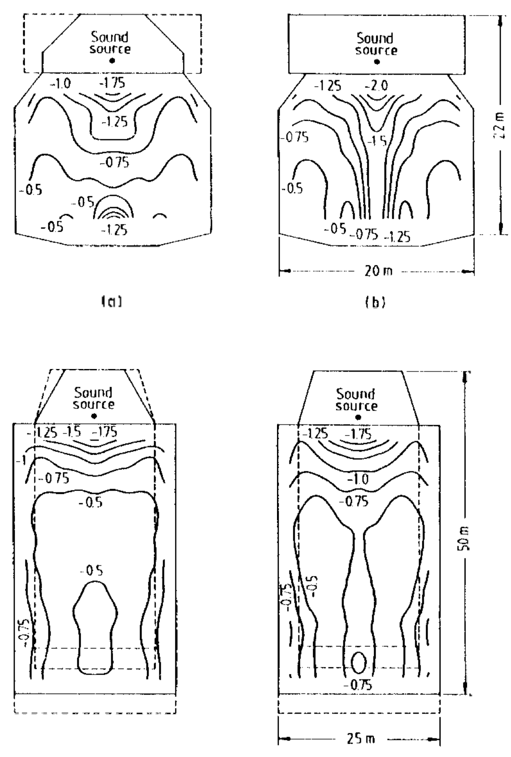

Fig. 5 Contour lines of total subjective preference calculated with four factors (Motif B) The auditrium at Kobe Univ. with stage reflector (a) and without (b), Boston (c,d)

Physiological Response from Brain

Fig. 6 indicates example of the auditory evoked potential obtained by averaging 50 responses for a single subject, as a function of the delay time of the single reflection. The electrical responses were obtained from the left and right temporal areas (T_3 and T_4) according to the International 10-20 System. In order to compare the feature of AEPs with the subjective preference, paired-stimuli method was applied changing each physical factor. In this figure, the amplitude of the reflection was the same as that of the direct sound. The source signal was a fragment of continuous speech "SOKI-BAYASHI" (Japanese) of 0.9 s. The reference sound field was only the direct sound without any time delay of reflection, but the sound pressure level was kept constant throughout. Also, two loudspeakers were located in front of the listener, so that the IACC was kept at a constant value of unity.

From this figure, the maximum latency of AEP was found at the delay time of 25 ms. This delay time well corresponds to the most preferred delay time of reflection relating to the effective duration of ACF of the speech signals.

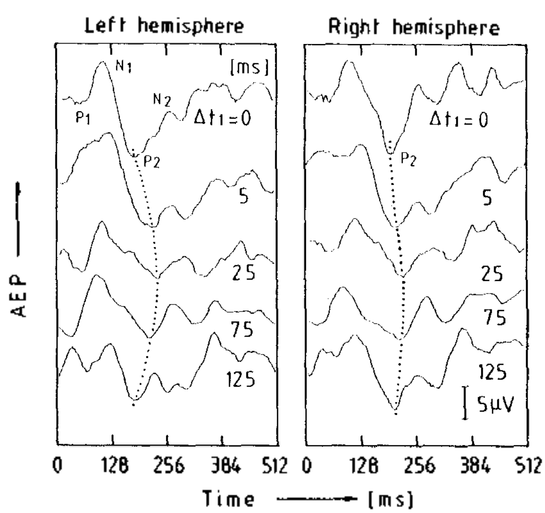

Fig. 6 Example of AEPs

Fig. 7 shows amplitudes of early AEP as a function of the delay time of the single reflection. The value averaged for 8 subjects is ptotted. The solid line indicates the amplitude from the left hemisphere and dashed line is that from the right hemisphere. Obviously, the amplitude

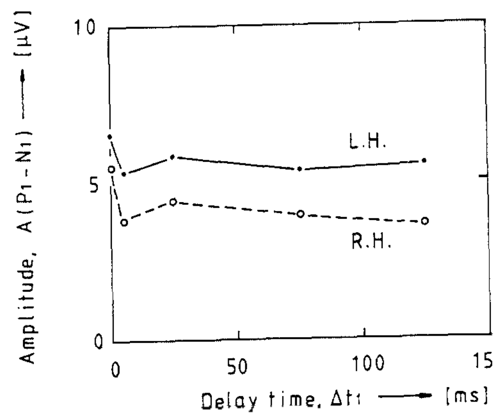

Fig. 7 Amplitudes of AEP from the left and right human cerebral hemispheres, when the delay time of the reflection is changed in the pair.

Table I Hemispheric dominance observed in the peak-to-peak amplitude of SVR, $A(P_1 - N_1)$.

Source signal	Parameter adjusted	$A(P_1 - N_1)$	P
Speech (0.9 s)	SL	R > L	< 0.01
Speech (0.9 s)	Δt_1	L > R	< 0.01
Speech vowel /a/	IACC	R > L	< 0.025
1/3 Oct. Band Noise (500 Hz)	IACC	R > L	< 0.05

from the left is much greater than that from the right indicating the left hemisphere "dominance".

Under the conditions of different physical factors changed, hemispheric dominaces are listed in Table I. It is quite remarkable that hemispheric dominaces differ according to the factor changed. For example, with the continuous speech signal, the right hemisphere is dominant under the condition of varying the sensation level, but the left is dominant under the delay time changing. If the IACC is changed, the right hemisphere is highly activated.

Fig. 8 shows relationship between the latency of AEP and the scale value of preference. Results of the scale value of subjective preference are indicated at the upper parts of this figure. And, the lower parts indicate the latency of AEP. Solid curves indicate the activities from the left hemisphere and dashed curves from right.

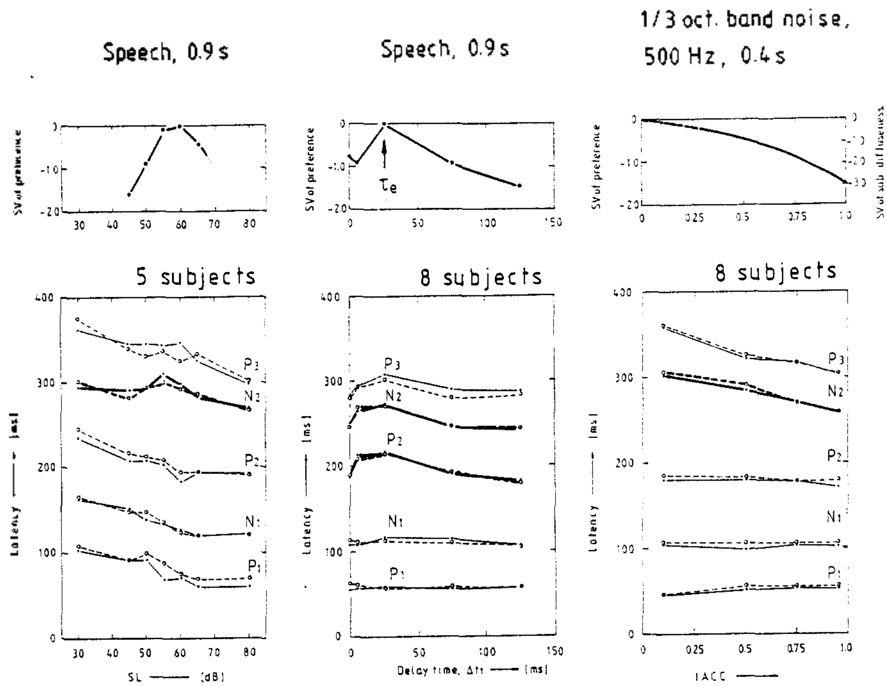

Fig. 8 Relationship between latencies of AEP and subjective preference (or subjective diffuseness against the IACC)

From the center column of this figure, the information related to subjective preference appeard in N_2 - latency around 260 ms, and the left column arround 300 ms for SL changed.
The right column shows effects of the IACC with the 1/3 oct. band noise centered on 500 Hz.
At the upper part, the scale value of subjective diffuseness is indicated as a function of IACC.
The scale value of subjective preference also has the similar tendency against the IACC when speech and music are presented.

Next, if we look at the behavior of early latencies of P_1 and N_1. These are almost constant when the delay time and the IACC are changed. However, the information related to the sensation level may be found typically at the N_1 - latency. This tendency agrees well with the results by Botte, Bujas and Chocholle appeared on the JASA in 1975.

Since the information related to the subjective preference appears in AEPs, it seems that subjective preference is traced back to a primitive subjective attribute in the "inner universe".

Model of Auditory-Brain System

In addition to AEP, we recorded auditory brainstem response (ABR) in ralation to the horizontal angle of sound incidence with a short pulse signal (50 μs). it is discussed that a possible interaural crosscorrelation mechnism at the inferior colliculus in the auditory pathways.

Considering this fact and above mentioned AEPs including the cerebral hemisphere dominace, we may construct a model of auditory-brain system as shown in Fig. 9.

In this model, the left hemisphere is mainly associated with temporal factors based on the ACF, and the right hemisphere deeply related to the spatial sound field based on the interaural cross correlation mechanism. This suggests that acoustic design should be performed by making both of human brains' satisfaction of temporal and spatial factors.

This level of concept may be applied for the design of any physical environment taking the temporal and spatial criteria.

For example, speech intelligibility and clarity depend not only on the temporal factor but on the IACC (Nakajima 1992). Any subjective attribut must be investigated with both spatial and temporal ones.

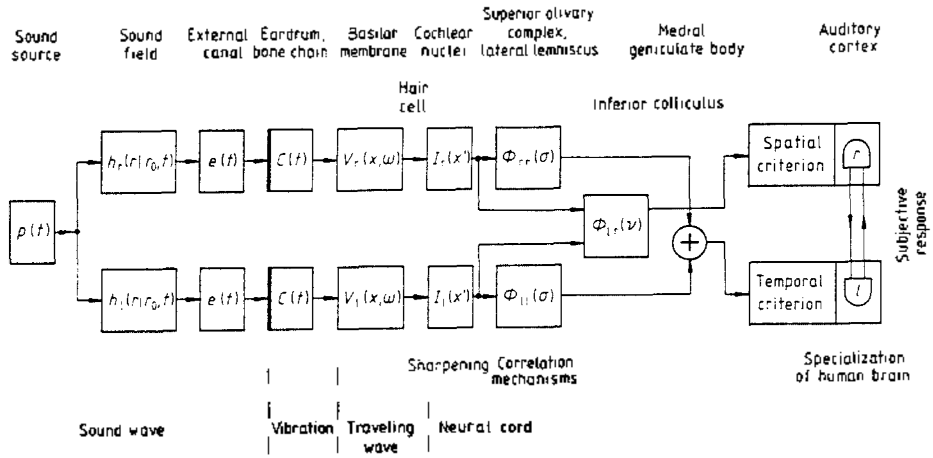

Fig. 9 Model of auditory-brain system

References

Y. Ando, Concert Hall Acoustics, Springer-Verlag, Heidelberg, New York (1985)

Y. Ando, S.H. Kang and K. Morita, J. Acoust. Soc. Jpn (E) 8 (1987) 197-206

Y. Ando, S.H. Kang and H. Nagamatsu, J. Acoust. Soc. Jpn(E) 8 (1987) 183-190

Y. Ando, Acustica 76 (1992) 292-296

Y. Ando, K. Yamamoto, H. Nagamatsu and S.H. Kang, Acoustics Letters 15 (1991) 57-64

M.C. Botte, Z. Bujas and R. Chocholle, J. Acoust. Soc. Am. 58 (1975) 208-213

T. Nakajima, "Speech Intelligibility and Clarity related to Spatial-Binaural Factor for Sound Field in a Room," PhD Dissertation, Graduate School of Science and Technology, Kobe University (1992)