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博士論文

On the subjective responses based on the auditory-brain model in relation to the factors extracted from the interaural cross-correlation mechanism and the auto-correlation mechanism of sound fields

聴覚大脳系のモデルに基づく音場の心理的反応に関する研究

- 相互相関メカニズムおよび自己相関メカニズムから抽出されたファクターに基づく評価 -

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Preface

This dissertation is submitted, for the Doctor of Philosophy degree, to Graduate School of Science and Technology, Kobe University, Japan.

This dissertation attempts to reveal the relationship between the subjective attributes for sound field and the factors extracted from the interaural cross-correlation function and autocorrelation function, based on the model of auditory-brain system.

I assume responsibility for any errors which may occur in the pages which follow.

Shin-ichi Sato

Acknowledgments

I take this opportunity to express my thanks to the many people who have helped me, in various ways, to attain my objective of preparing this dissertation. I would like to express my gratitude for the considerable guidance and encouragement received from Professor Yoichi Ando, Kobe University, whose contribution to this research has been substantial. I also wish to express appreciation to Professor Hiroshi Kawamura and Professor Takaji Matsushima, Kobe University.

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Finally, the generous support of Japan Society for the Promotion of Science, since 1996, enabled me to concentrate on the research necessary to complete this dissertation.

Shin-ichi Sato

Contents

Chapter 1

Introduction

1.1. General Preface

To produce an excellent sound field in a concert hall, it is necessary to find the significant physical factors on the subjective attributes. Sound signals proceed along auditory pathways and the meanings of the signals are interpreted by the brain. If enough were known about the auditory cognitive system in the brain, the design of concert halls could proceed according to guidelines derived from the knowledge of this system. The auditory-brain model proposed here is consists of the interaural cross-correlation mechanism between the two auditory pathways, the autocorrelation mechanisms, and the specialization of human cerebral hemispheres for temporal and spatial factors of the sound field. Subjective preference for sound fields can be calculated from the four orthogonal physical factors of the temporal and spatial factors. This study tries to reveal the relationship between the other subjective attributes (image shift of sound source and apparent source width, ASW) for sound field as well as subjective preference and the factors extracted from the interaural cross-correlation function and autocorrelation function, based on the model of auditory-brain system. The final goal of the study is to calculate the these subjective attributes at each seat in concert halls.

1.2. Previous Studies

1.2.1. Subjective preference for sound fields

To realize an excellent sound field in a concert hall, it is important to identify the orthogonal factors influencing subjective evaluation. Using dissimilarity tests, Yamaguchi (1972) found two significant physical factors, the sound pressure level and the reverberation characteristics. Edward (1974) also tested dissimilarity, and reported the early-echo pattern, the reverberation time RT, and the volume level to be the significant factors. Schroeder et al. (1974) avoided using ill-defined adjectives, such as "intimate", "warm", "rich", and "clear", by conducting subjective preference tests. They found two significant factors, RT and the interaural cross-correlation (IACC), defined by Damaske and Ando (1972). Kimura and Sekiguchi (1976) found reverberance and loudness to be significant factors. Wilkens (1977) found that perception of strength and extension of sound source, perception of clarity, and tone color are significant subjective attributes. Systematic investigations by Ando were made to find the orthogonal factors in subjective preference for sound fields (Ando, 1985). Ando described four orthogonal physical factors (the listening level LL, the initial time delay gap Δt_1, the subsequent reverberation time T_{sub}, and the IACC), that determine the scale values of subjective preference for simulated sound fields. From subjective questionnaires, Barron found that the reverberation time, the early decay time, the early-to-late sound index C_{80}, the total sound level, and the early lateral energy fraction were significant subjective factors (Barron, 1988; Barron, 1994). Beranek (1996) suggested adding two more factors to Ando's four physical factors, the Bass ratio (BR) and the Surface Diffusivity Index (SDI). Problems with regard to both objective and subjective orthogonalities in above two investigations still remain. As far as subjective preference is concerned, it is worth noting that the sound fields in a real concert hall of listeners facing to the performers ($\tau_{IACC} = 0$) can be described by only four orthogonal physical factors (Ando, 1985; Cocchi et al., 1990).

In addition, we need to design the sound fields in stage area as well as in the audience area. The primary issue is that the stage enclosure should be designed to provide a sound field in which performers can play easily. Marshall et al. (1978) investigated the effects of stage size on the playing of an ensemble. The parameters related to stage size in their study were the delay time and the amplitude of reflections. Gade (1989) used a laboratory experiment to investigate the preference of performers for the total amplitude of the reflections. On the other hand, the preferred delay time of a single reflection for listeners can be calculated from the effective duration of the long-time autocorrelation function of the source signal and the amplitude of reflections (Ando, 1977; Ando and Kageyama, 1977; Ando, 1998). When music signals contain a large fluctuation in tempo, it is more accurately expressed by the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of source signal (Ando et al., 1989). Nakayama (1984) showed that the preferred delay time of a single reflection for alto-recorder soloists can be determined from the amplitude of the reflection and the duration of the long-time autocorrelation function of the source signal.

1.2.2. Subjective attributes for spatial factors

First, the importance of the spatial attributes of sound field was discussed in terms of the shape or cross section of the concert halls (Marshall, 1978a,b).

Keet (1968) reported that the absolute ASW for each fixed listening level is strongly correlated to the cross-correlation function measured using two cardioid microphones with a 90° angle between. Barron (1971) described the importance of early lateral reflections for spatial impression, and claimed that the degree of spatial impression is related to the ratio of lateral to non-lateral sound arriving within 80 ms of the direct sound. Damaske and Ando (1972) defined IACC as the maximum absolute value of the interaural cross-correlation function lying within the possible maximum interaural time delay range, and reported that IACC corresponds to the subjective diffuseness of the sound field.

Later, it was determined that IACC is a significant factor for the subjective preference in sound fields. Schroeder et al. (1974) conducted the subjective preference tests and found two significant factors, reverberation time RT and IACC. From the systematic investigations in simulated sound field, Ando (1985) found the four orthogonal acoustic factors (the listening level LL, the initial time delay gap Δt_1, the subsequent reverberation time T_{sub}, and the IACC), which determined the scale values of subjective preference for sound fields. Beranek (1996) also proposed that the IACC is the one of his proposed six significant factors.

Another spatial factor, Lateral Energy Fraction defined from the experiment conducted by Barron and Marshall (1981) was proposed, however, the reflection arriving from 90° in the horizontal plane is not always advantages increasing the subjective diffuseness.

The ASW is also known to be related to IACC. Morimoto and Maekawa (1988) reported that low frequency component of the source signal increase the auditory spaciousness. Morimoto (1995) reported that ASW corresponds to IACC measured without frequency weighting. However, the ASW depends on the center frequency of the bandpass noise. When the values of IACC for the octave bandpass noise are equal, ASW increases, as the center frequency becomes lower . Hidaka et al. (1995) also reported that IACC for each fixed ASW increases at a lower frequency.

1.2.3. Physiological responses for sound fields

In order to confirm the possible mechanism, left and right auditory brainstem responses (ABR) were confirmed in the sound field changing the incident angle of sound in horizontal angle (Ando et al., 1992). The neural activity (wave V) may correspond to the IACC; thus, the interaural cross-correlation mechanism may exist at the inferior colliculus.

It is quite natural to assume that the fundamental subjective attributes are reflected by brain activity or physiological responses. The relationship between the slow vertex response (SVR) and subjective preference has been investigated systematically (Ando, 1992). The SVR was recorded by averaging the evoked potentials responding to auditory stimuli, such as clicks, noise and speech. An adjustable test stimulus was presented alternately with a reference stimulus. The pair of stimuli was presented 50 times to integrate and average the evoked potentials, and the SVRs were obtained from the left and right temporal area (T3, T4: according to the International 10-20 system (Jasper, 1958)). The results show that the latency of N_2-components, that is, the interval between the time the stimulus was presented and the time of the second negative peak of the SVR, corresponded significantly to the subjective preference for changes of the sensation level SL, the delay time of single reflection Δt_1, and the IACC, respectively (Ando et al., 1987; Ando et al., 1987). The longest latencies are always observed for the most preferred condition, revealing that most of the brain is relaxed under the preferred condition. Furthermore, it is remarkable that hemispheric dominance appeared in the amplitude of the early stage of the SVR. In the results the amplitude of $A(P_1\text{-}N_1)$, which is the amplitude of the first positive peak to the first negative peak, shows that the hemispheric dominance differed as acoustic factors changed. The left hemisphere was dominant when the Δt_1 was varied and the right hemisphere was dominant when SL or IACC were varied.

The evoked-potential methods cannot be applied to changes of the reverberation time with signals longer than 0.9 s, therefore a method for analyzing a continuous brain wave was developed. When a pair of stimuli are presented, the continuous brain wave can be recorded. The effective duration of autocorrelation function, τ_e, of the α-waves for the continuous brain wave was analyzed for changes in the delay time of the single reflection and the reverberation time, respectively. It is noteworthy that the τ_e of α-waves are longer only in the left hemisphere for the preferred conditions $[\Delta t_1]_p$ and $[T_{sub}]_p$ (Ando and Chen, 1996; Chen and Ando, 1996).

This may be interpreted as being caused by a similar repetitive feature in the α-waves evoking comfortable relaxation repeatedly in the mind.

Thus, the subjective preference can be traced back to a primitive response seen as gross brain activity that corresponds well with the scale value of subjective preference. Also, the evidence indicates that the left hemisphere dominance of the temporal factors (Δt_1, T_{sub}) and the right hemisphere dominance of the spatial factors (IACC and SL) may independently influence subjective preference values (Nishio and Ando, 1996).

1.3. Model of Auditory-Brain System

According to the subjective attributes, and phenomena on the auditory evoked potentials including CBW in the change of acoustic factors, the model of auditory-brain system may be proposed as shown in Figure 1.1. The sound source $p(t)$ in this figure is located at a point r_0 in a three-dimensional space, and the listener sitting at r is defined by the location of the center of the head, $h_{l,r}(r|r_0,t)$, being the impulse responses between r_0 and the left and right ear-canal entrances. The impulse responses of the external ear canal and the bone chain are respectively $e_{l,r}(t)$ and $c_{l,r}(t)$. The velocities of the basilar membrane are expressed by $V_{l,r}(x,\omega)$, x being the position along the membrane. The action potentials from the hair cells are conducted and transmitted to the cochlear nuclei, the superior olivary complex (including the medial superior olive, the lateral superior olive and the trapezoid body), and to the higher level of two cerebral hemispheres.

The input power density spectrum of the cochlea $I(x')$ can be roughly mapped, according to the tuning of a single fiber (Katsuki et al., 1958; Kiang, 1965), at a certain nerve position x'. This fact may be partially supported by ABR waves (I - IV) which reflect the sound pressure levels as a function of the horizontal angle of incidence to a listener. Such neural activities, in turn, include sufficient information to produce the autocorrelation function at a higher level, probably near the lateral lemniscus as indicated by $\Phi_{ll}(\sigma)$ and $\Phi_{rr}(\sigma)$, where σ corresponds to the neural activities. For convenience, the interchange of neural signals is not included here. The neural activity (wave V) may correspond to the IACC (Ando et al., 1992). Thus, the interaural cross-correlation mechanism may exist at the inferior colliculus. It is concluded that the output signal of the interaural cross-correlation mechanism including the IACC and the loci of maxima may be dominantly connected to the right hemisphere. The sound pressure level may be expressed by a geometrical average of autocorrelation functions for the two ears at the time of origin ($\sigma = 0$) which in fact appearing in the latency at the inferior colliculus may be processed in the right hemisphere. Effects of the initial time delay gap between the direct sound and the single reflection Δt_1 included in the autocorrelation function may activate the left hemisphere. Such specialization of the human cerebral hemisphere may be related to the highly independent contributions of spatial and temporal criteria to subjective attributes.

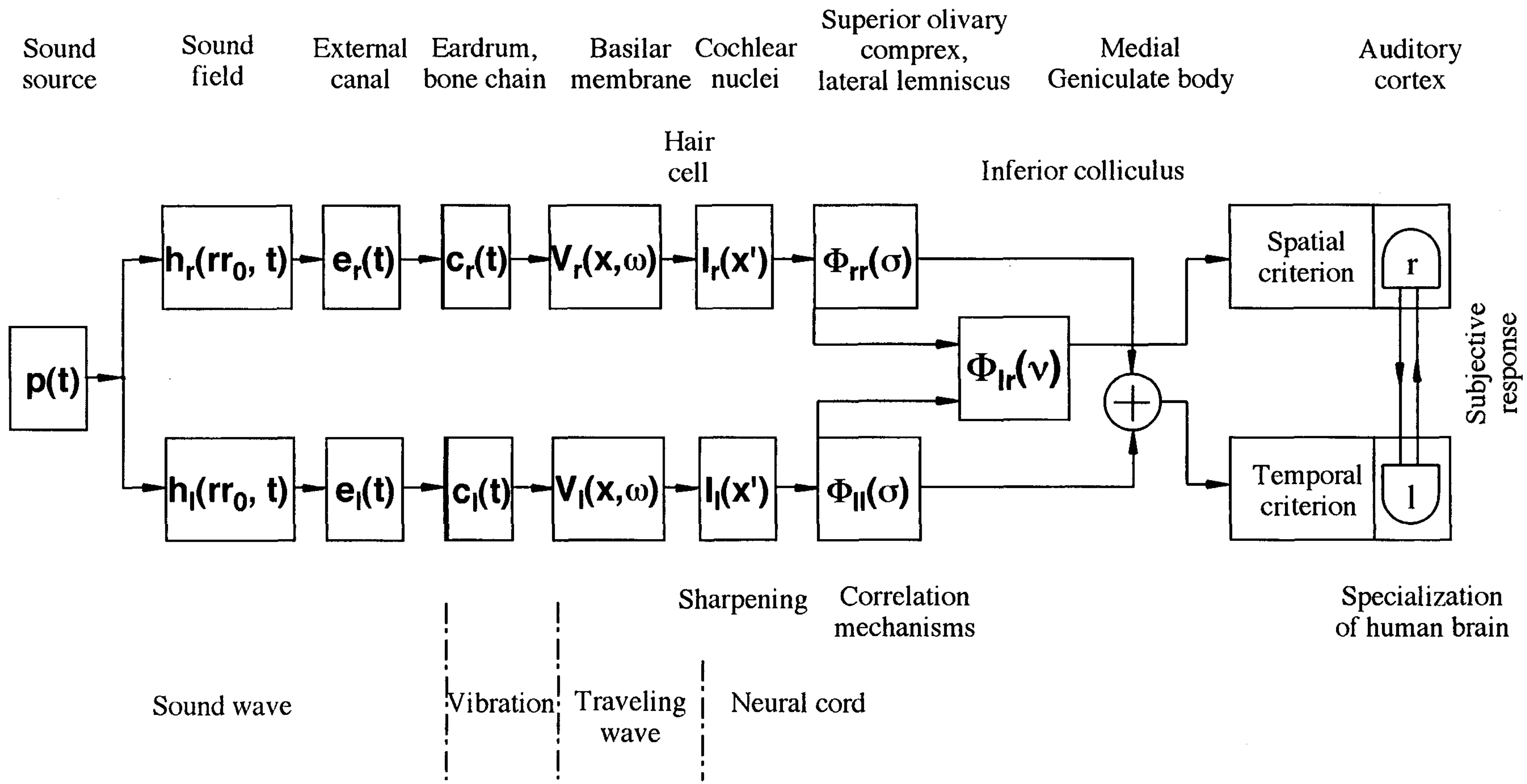


Figure 1.1. An auditory-brain model for subjective responses.

1.4. Spatial Factors extracted from the Interaural Cross-correlation Function

In the auditory-brain model proposed, interaural cross-correlation mechanism between the two auditory pathways is assumed. The fundamental spatial attributes for sound field may be related to the interaural cross-correlation function. The interaural cross-correlation function between the sound signals at both ears, $f_l(t)$ and $f_r(t)$, is defined by

$$\Phi_{lr}(t) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} f_l'(t) f_r'(t+\tau) dt, \qquad |\tau| \leq 1 \text{ ms} \tag{1.1}$$

where $f_l'(t)$ and $f_r'(t)$ are approximately obtained by signals $f_{l,r}(t)$ after passing through the A-weighting network, which corresponds to the ear sensitivity, $s(t)$. The external and the middle ear may characterize the ear sensitivity.

The normalized cross-correlation function is defined by

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)}} \tag{1.2}$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are, respectively, the autocorrelation functions at $\tau = 0$ for the left and right ears, and thy are the sound energies arriving at both ears. If discrete reflections arrive after the direct sound, then the normalized interaural cross-correlation is expressed by

$$\phi_{lr}^{N}(\tau) = \frac{\sum_{n=0}^{N} A^2 \Phi_{lr}^{n}(\tau)}{\sum_{n=0}^{N} A^2 \Phi_{ll}^{n}(0) \sum_{n=0}^{N} A^2 \Phi_{rr}^{n}(0)}, \tag{1.3}$$

where we put $\omega_n(t) = \delta(t)$, and $\Phi_{lr}^{n}(\tau)$ is the interaural cross-correlation of the n th reflection, $\Phi_{ll}^{n}(0)$ and $\Phi_{rr}^{n}(0)$ are the respective sound energies arriving at the two ears from the n th reflection.

When the sound source is located at any horizontal angle ξ relative to the frontal direction to a listener's head, and the bandpass noise, after passing through an ideal filter with upper and lower frequencies of f_2 and f_1, is radiated from the source location, then the interaural cross-correlation function and the autocorrelation function at $\tau = 0$ are given by

$$\Phi_{lr}(\tau) = H_{lr}[\frac{2}{\Delta\omega(\tau - \tau_{\xi})}]\sin[\frac{\Delta\omega(\tau - \tau_{\xi})}{2}]\cos[\frac{\Delta\omega_c(\tau - \tau_{\xi})}{2}],$$

$$\Phi_{ll}(0) = H_{ll}$$

$$\Phi_{rr}(0) = H_{rr} \tag{1.4}$$

where H_{lr} is the cross power of the bandpass noise, H_{ll} and H_{rr} are the auto powers at the two ear entrances, τ_{ξ} is the maximum interaural delay depending on ξ, and

$$\Delta\omega_c = 2\pi(f_2 + f_1),$$

$$\Delta\omega = 2\pi(f_2 - f_1). \tag{1.5}$$

Independent factors extracted from the interaural cross-correlation function are defined in Figure 1.2. There are four significant factors:

(1) Magnitude of the interaural cross-correlation IACC is defined by

$$\mathrm{IACC} = |\phi_{lr}(\tau)|_{\max} \tag{1.6}$$

for the possible maximum interaural time delay, say, $|\tau| \leq 1$ ms. A smaller value of the IACC is better for all of the subjects investigated (Ando, 1998).

(2) Interaural delay time τ_{IACC} at which the IACC is defined, is a significant factor in determining the perceived horizontal direction of the sound field of the sound field or image shift (Damaske and Ando, 1972).

(3) Width of the interaural cross-correlation function W_{IACC}, which is defined by the time interval between δ-values, corresponding to the just noticeable difference of the IACC, below the IACC of the source signal. The W_{IACC} of bandpass noise after passing through an ideal filter is given by (Ando, 1998)

$$W_{\mathrm{IACC}}^{(\delta)} \approx \frac{4}{\Delta\omega_c}\cos^{-1}\left(1 - \frac{\delta}{\mathrm{IACC}}\right). \tag{1.7}$$

For simplicity, the value of δ is defined by 0.1(IACC) in this study.

(4) Geometrical mean of the sound energies at both ears which is defined by the denominator of Equation (1.2),

$$\sqrt{\Phi_{ll}(0)\Phi_{rr}(0)} \tag{1.8}$$

The sound pressure level also affects ASW (Keet, 1968). The sound signal is send to only one ear in case of headphone listening, for example, the value of Equation (1.8) becomes zero. This factor can be applied when the sound source is located in a three dimensional space. For headphone listening, the sound pressure level at eardrum should be measured.

A well-defined direction is perceived when the normalized interaural cross-correlation function has one sharp peak maximum (a small value of W_{IACC}). On the other hand, subjective diffuseness or no spatial impression corresponds to a low value of the IACC (< 0.15). These four factors are independently related to the spatial subjective attributes, for example, subjective diffuseness, apparent source width, and the image shift.

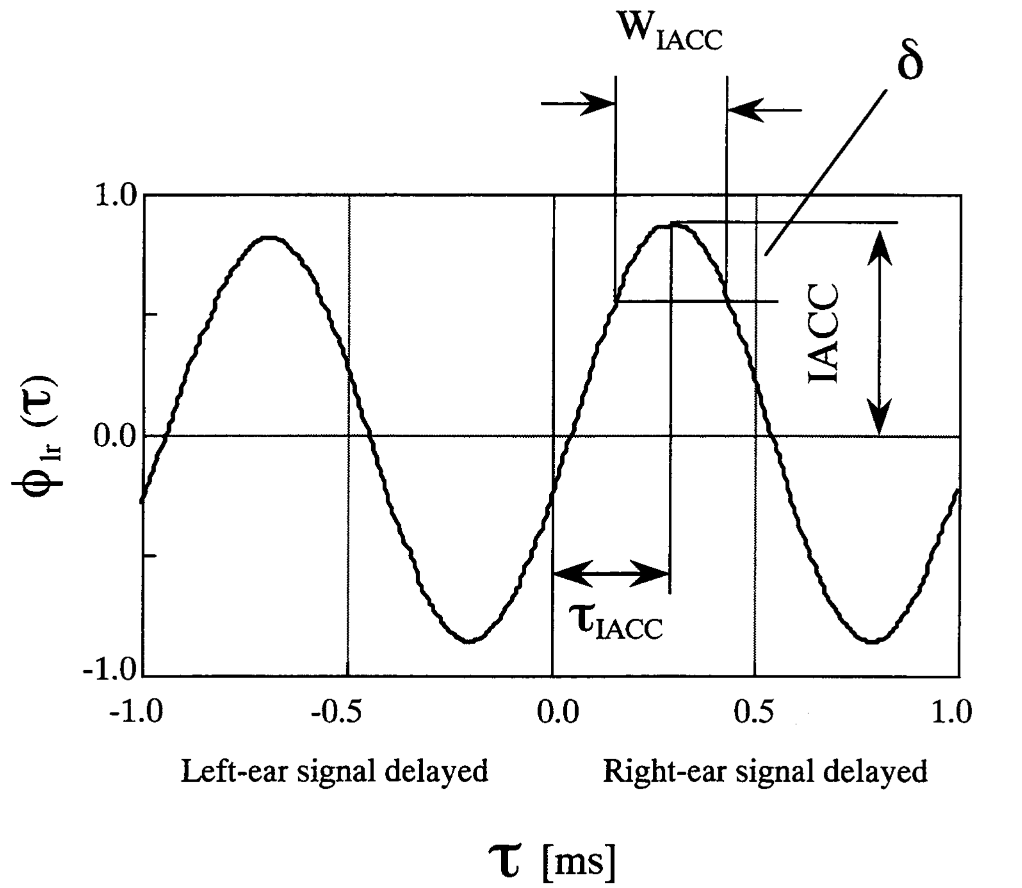


Figure 1.2. Definition of the IACC, τ_{IACC}, and W_{IACC} for the interaural cross-correlation function.

1.5. Temporal Factors extracted from the Autocorrelation Function

The power density spectra in the neural activities in the left and right auditory pathways have a sharpening effect (Katsuki et al., 1958; Kiang, 1965). This information is enough to attain the approximation of autocorrelation functions of the signals at both ears.

The autocorrelation function is defined by

$$\Phi_p(\tau) = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T} p'(t)p'(t+\tau)dt, \tag{1.9}$$

where $p'(t) = p(t) * s(t)$, $s(t)$ being the ear sensitivity. For convenience, $s(t)$ may be chosen as the impulse response of an A-weighted network.

The autocorrelation function is identical to the power density spectrum $P_d(\omega)$, so

$$\Phi_p(\tau) = \int_{-\infty}^{+\infty} P_d(\omega)e^{j\omega t}dt \tag{1.10}$$

and

$$P_d(\omega) = \int_{-\infty}^{+\infty} \Phi_p(\tau)e^{-j\omega t}d\tau, \tag{1.11}$$

Thus, the autocorrelation function and the power density spectrum mathematically contain the same information. In autocorrelation function analysis, there are three significant parameters:

(1) Energy represented at the origin of the delay, $\Phi_p(0)$.

(2) Effective duration of the envelope of the normalized autocorrelation function, τ_e (which is defined by the ten-percentile delay), representing a kind of repetitive feature or reverberation containing the source signal itself as shown in Figure 1.3(a). The normalized autocorrelation function is defined by

$$\phi_p(\tau) = \frac{\Phi_p(\tau)}{\Phi_p(0)}. \tag{1.12}$$

(3) Fine structure, including peaks and dips with their delays. The delay time and amplitude of the first peak – namely, τ_1, and ϕ_1 as shown in Figure 1.3(b) – may represent this structure. These values τ_1 and ϕ_1 are usually thought to be closely related to τ_n and ϕ_n ($n > 1$), which are the delay time and amplitude of the nth peak.

When the signals contain a large fluctuation in tempo, it is more accurately expressed by applying the running autocorrelation function of source signal (Ando, et al., 1989).

The running autocorrelation function as a function of time t is calculated as

$$\begin{aligned}\phi_p(\tau) &= \phi_p(\tau;t,T) \\ &= \frac{\Phi_p(\tau;t,T)}{[\Phi_p(0;t,T)\Phi_p(0;\tau+t,T)]^{1/2}},\end{aligned} \tag{1.13}$$

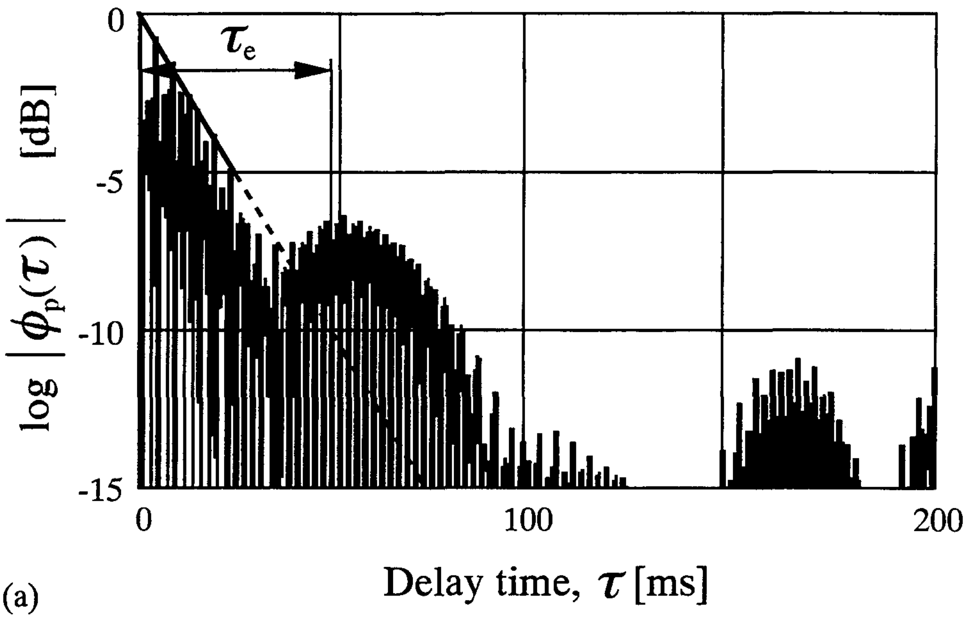
where

$$\Phi_p(\tau;t,T) = \frac{1}{2T}\int_{t-\tau}^{t+\tau} p'(s)p'(s+\tau)ds. \tag{1.14}$$

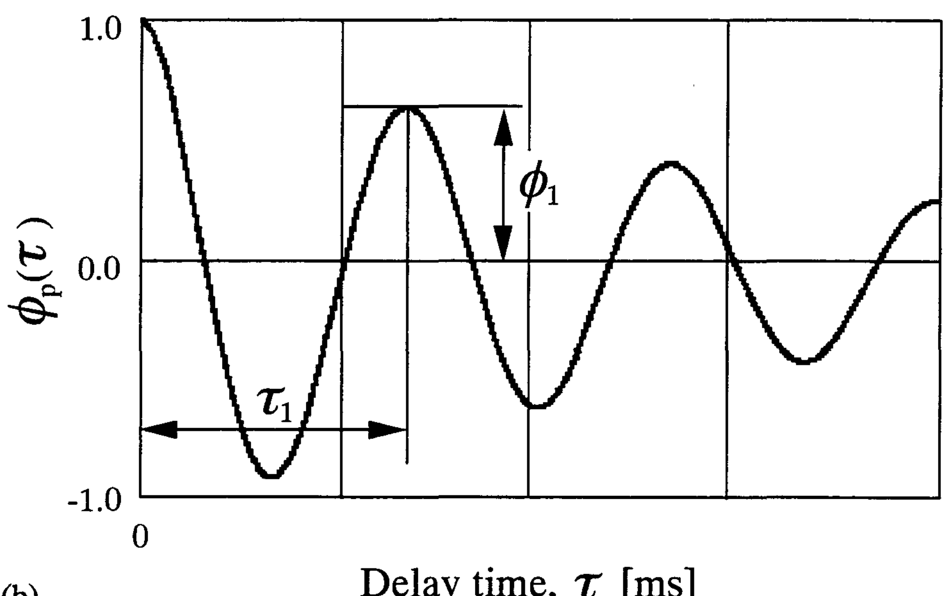
The normalized autocorrelation function satisfies the condition that $\phi_p(0) = 1$.

Figure 1.3(a) demonstrates an example of the logarithm of the absolute value of the autocorrelation function plotted as a function of the delay time. The envelope decay of the initial part of the autocorrelation function can be fitted by a straight line in the range from 0 dB to -5 dB, and the effective duration τ_e of the autocorrelation function can be easily obtained from the decay rate extrapolated at -10 dB (Ando and Chen, 1996).

The signal duration 2T corresponds to the psychological present, as suggested by Fraisse (1982), is 2T = 0.5-5.0 s. The psychological present defined here is a short time duration of stimuli needed for subjective responses. The minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of a music signal which is the most active part of the music signal contains important information and influences the subjective attributes related to the temporal factors.



(a)



(b)

Figure 1.3. Definitions of factors extracted from the normalized autocorrelation function, (a) τ_e ; and (b) τ_1 and ϕ_1.

1.6. Aim of This Study

From the previous studies, it was found that the magnitude of the interaural cross-correlation function (IACC) is correlated to the subjective preference or subjective diffuseness and that the spatial subjective attributes can be described by the factors extracted from the autocorrelation function. In this study, image shift of sound source and apparent source width (ASW) are discussed as well as subjective preference. These factors cannot be described by only IACC, therefore, the factors extracted from the interaural cross-correlation function, that is, the interaural time delay τ_{IACC} and the width of the interaural cross-correlation function W_{IACC} are introduced.

For calculating the scale value of subjective preference, the IACC must be obtained at the $\tau_{IACC} = 0$ to ensure frontal localization of the sound source, however, the IACC in existing sound field was not always maintained at $\tau_{IACC} = 0$ due to the sound source locations. Therefore, the effect of the τ_{IACC} on subjective preference was confirmed in chapter 2. The relationship between the subjective preference and the image shift of the source signal and the interaural time delay of IACC (τ_{IACC}) is examined. In addition, the theory calculating the subjective preference was reconfirmed in existing sound field.

The IACC is correspond to the subjective preference or subjective diffuseness. Even if the IACC is constant, the ASW increases as the center frequency of octave band noise become lower or as the lower frequency component increase. These facts are reflected in the interaural cross-correlation function. The peak of the function become broader as the center frequency of octave band noise become lower. Chapter 3 deals with the relationship between the apparent source width (ASW) and the W_{IACC} as well as the IACC. It was examined whether or not the scales value of ASW for noise signals and a music signal obtained by the paired comparison tests can be calculated by the two dimensional factors, IACC and W_{IACC}.

In chapter 4, subjective preference of cellists for the delay time of a single reflection was examined. The preferred delay time of the reflection for listener is related to the autocorrelation function of source signal. It was examined that the preferred delay time of a single reflection for cellists can be calculated from the effective duration of the running autocorrelation function of the music motifs played by cellists. The scale values of preference for the delay time of a single reflection were obtained using a paired comparison method, and the results were compared with those for the alto-recorder players and listeners.

Chapter 2

Subjective Preference and Image Shift in relation to the τ_{IACC} in existing Sound Fields

2.1. Introduction

As described in chapter 1.4, the interaural time delay τ_{IACC} related to the sound localization in horizontal plane or balance of sound field.

The maximum value of the interaural cross-correlation function must be maintained at $\tau_{IACC} = 0$ to ensure frontal localization of the sound source for calculating the scale value of preference, however, τ_{IACC} in a real concert is not always zero because of the source location on the stage. In this chapter, the subjective preference judgment for different source locations on the stage was performed by the paired-comparison tests at each set of seats, and the relationship between the scale value of subjective preference and physical factors obtained by simulation using architectural schemes is examined by the factor analysis. Also, the method of calculating the scale value of subjective preference of simulated sound field by use of four orthogonal physical factors (the listening level, the initial time delay gap, the reverberation time and the IACC) is reconfirmed for sound fields in an existing concert hall.

2.2. Preference Tests

For preference tests, a concert hall in Kobe (UHARA Hall) contains 650 seats with a volume of 4,870 m^3 was used. As a source signal Music motif B (Sinfonietta, Opus 48; third movement, composed by Arnold) was selected in the tests. As shown in Figure 2.1, four loudspeakers were placed at 0.8 m above the stage floor, and 64 listeners were divided into 21 groups and seated at the specified positions.

To excluding the effects of other physical factors such as visual and tactual senses on judgments, the subjective were asked in their seats and judge the preference by paired-comparison method, switching only the loudspeakers on the stage. The test consisted of 6 pairs (N(N-1)/2, N = 4) of stimuli, in total. The signal duration was 5 s, and the silent interval between stimuli was 1 s. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order. In order to obtain enough data, a contiguous three or four seats was used in a single test session. This session was repeated five times, with subjects changing seats between sessions, and 14 to 16 subjects in total responded at each set of seats. It took about 30 minutes.

The scale values of preference were obtained by applying the law of comparative judgment (case V; Thurstone, 1927), and were reconfirmed by the goodness of fit (Mosteller, 1951).

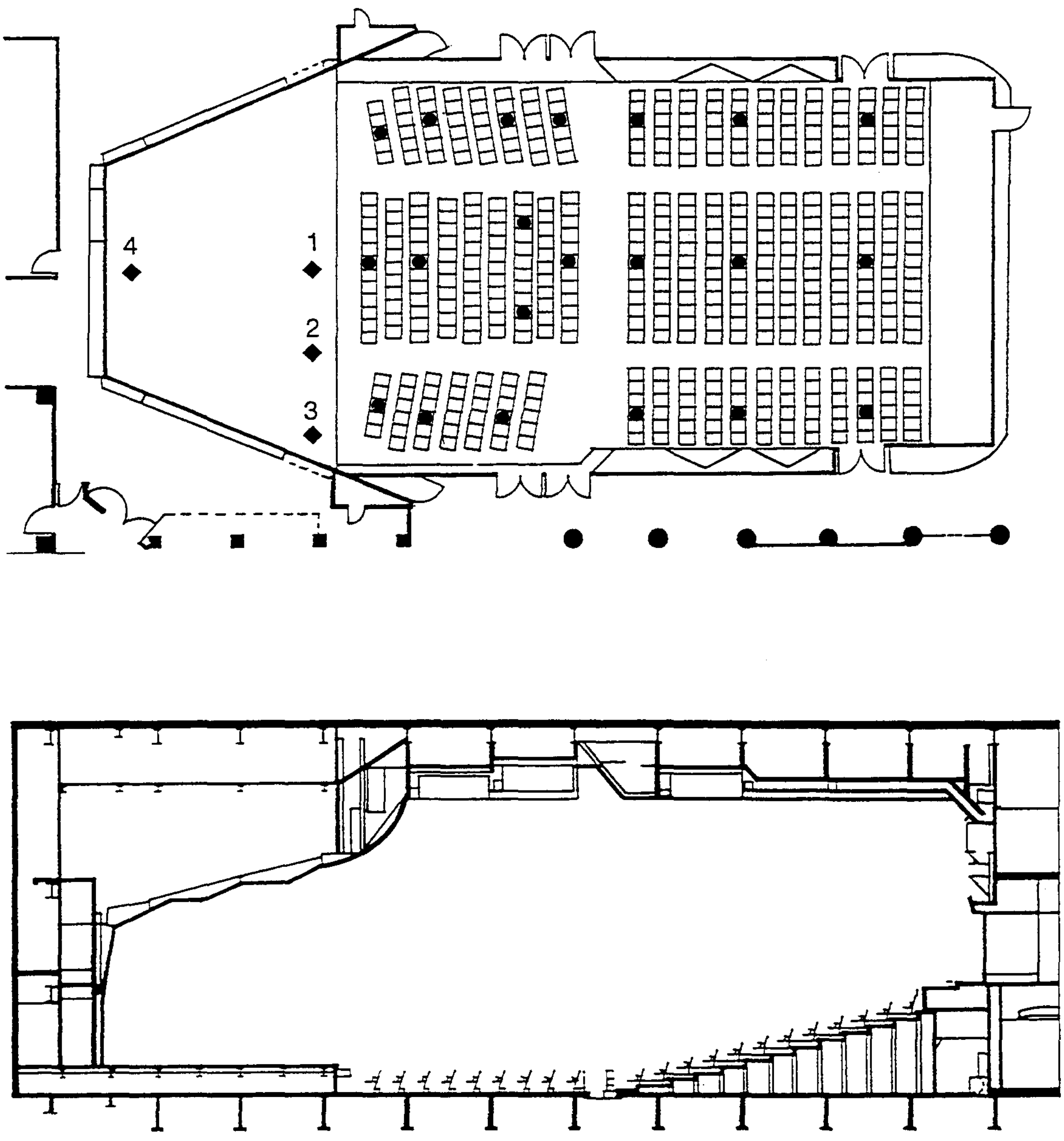


Figure 2.1. Plan and section of the hall (Uhara-Hall, Kobe). ◆ sound source (4 positions); ● Listener's location (21 positions).

2.3. Calculation of Physical Factors at Each Seat

The physical factors at each set of seats for four source locations on the stage were calculated. In the simulation, the directional characteristics of four loudspeakers used in preference tests were taken into consideration. The calculation was performed up to three times for each directional reflection to a listener. Due to a floor structure with fair amount of acoustic transparency, the floor reflection was not taken into account for calculation, and part of the diffuser ceiling was regarded as nonreflective plane for the sake of convenience. From the impulse response of each seats, the listening level and the subsequent reverberation time of each octave band center frequency and the initial time delay gap were calculated. The interaural cross-correlation functions for music motif B were also calculated. In calculation of the IACC, the listeners faced toward the center of the stage, so that the IACC does not always a maximum at the interaural time delay $\tau_{IACC} = 0$.

2.4. Multiple Dimensional Analysis

In order to examine the relationship between the scale values of subjective preference and physical factors obtained by simulation of an architectural scheme, the data were analyzed by the factor analysis described in Appendix A (Hayashi, 1952; Hayashi, 1954).

Of the four physical parameters, the reverberation time was almost constant for the source location and the seat location throughout the hall, and thus not involved in the analysis. As was previously discussed, for calculating the scale value of preference, the maximum value of the interaural cross-correlation function must be maintained at an interaural time delay $\tau_{IACC} = 0$ to ensure frontal localization of the sound source. However, the IACC was not always maintained at $\tau_{IACC} = 0$ due to the loudspeaker locations, because the subjects could not always be facing the source location. In this analysis, therefore, the effect of the interaural time delay, τ_{IACC} was added as an additional factor. Thus, the outside variable to be predicted with the factor analysis was the scale value obtained by subjective judgments and the explanatory factors were:

(1) the listening level;

(2) the initial time delay gap;

(3) the IACC; and

(4) the interaural time delay of IACC (τ_{IACC}).

2.5. Results and Discussion

Some iterations for the boundary of the each category of the factors were conducted. The boundary indicates the maximum correlation coefficient between the scale values obtained from the paired comparison test and the scores obtained from the factor analysis were applied to the results.

The scores for each category of the factors obtained from the factor analysis are shown in Figure 2.2. The scores of the listening level indicate a peak at the subcategory of 83 dB to 85.9 dB and decrease the score apart from the preferred listening level. For the IACC, the score increases with a decrease in the IACC. It is worth noticing that the scores of the above-mentioned two factors are in good agreement with the preference scale values obtained by preference judgments for a simulated sound field. The scores of the initial time delay gap which are normalized to the optimum value ($\Delta t_1 / [\Delta t_1]_p$) peaked at a smaller value than the most preferred value of the initial time delay gap obtained from the simulated sound fields. It is considered that, due to the limited range of Δt_1 in the existing concert hall and the limited data in the short range of the Δt_1, the effects of Δt_1 of the sound fields were rather minor in this investigation. Concerning τ_{IACC}, the score decreases monotonically as the τ_{IACC} is increased. This may caused by an image shift. The relationship between the scale value obtained by subjective judgments and the total score at each center of three or four seats is shown in Figure 2.3. The scale values of preference are well predicted with the total score for four loudspeaker locations ($r = 0.70$, $p < 0.01$).

It appears in occasions a certain degree of coherence between physical factors, for example, the calculated listening level and IACC for sound fields in existing concert halls as listed in Table 2.1. However, due to the fact that the factors are theoretically orthogonal, the preference scores obtained here are in good agreed with the calculated scale values which are obtained by simulating sound fields. This coherence is the physical phenomena depend on the characteristics of the sound field. It is confirmed that the results of the scores after removed the data of five seats in front of the hall changed slightly, however, the relationship between sub-categories does not change.

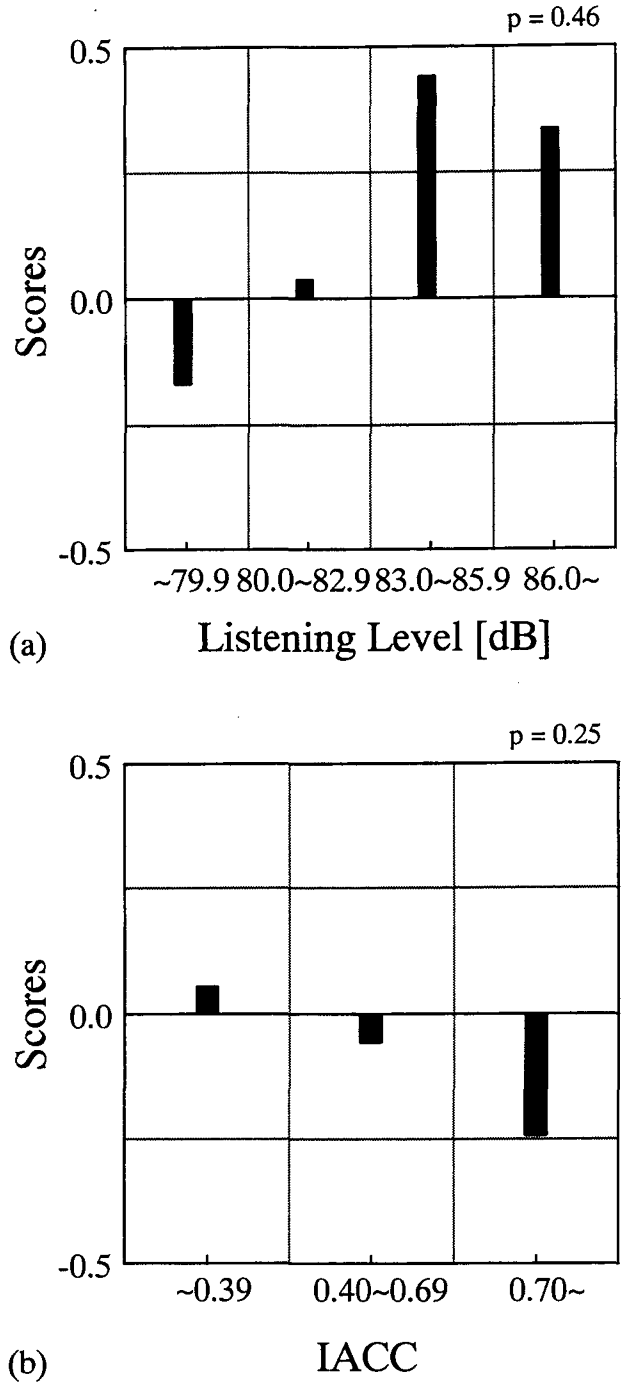


Figure 2.2. Scores for each category of four physical factors obtained by factor analysis: (a) the listening level; (b) the initial time delay gap (p: partial correlation of each item).

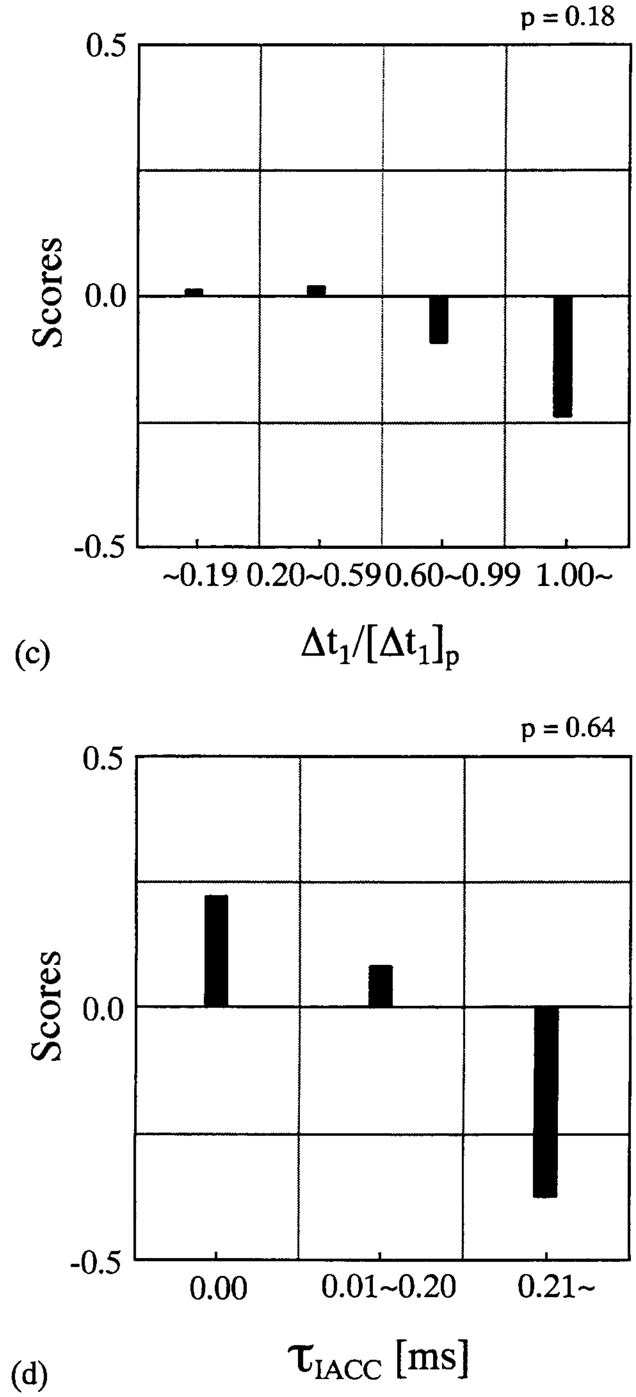


Figure 2.2. Scores for each category of four physical factors obtained by factor analysis: (c) IACC; and (d) the interaural time delay of IACC (p: partial correlation of each item).

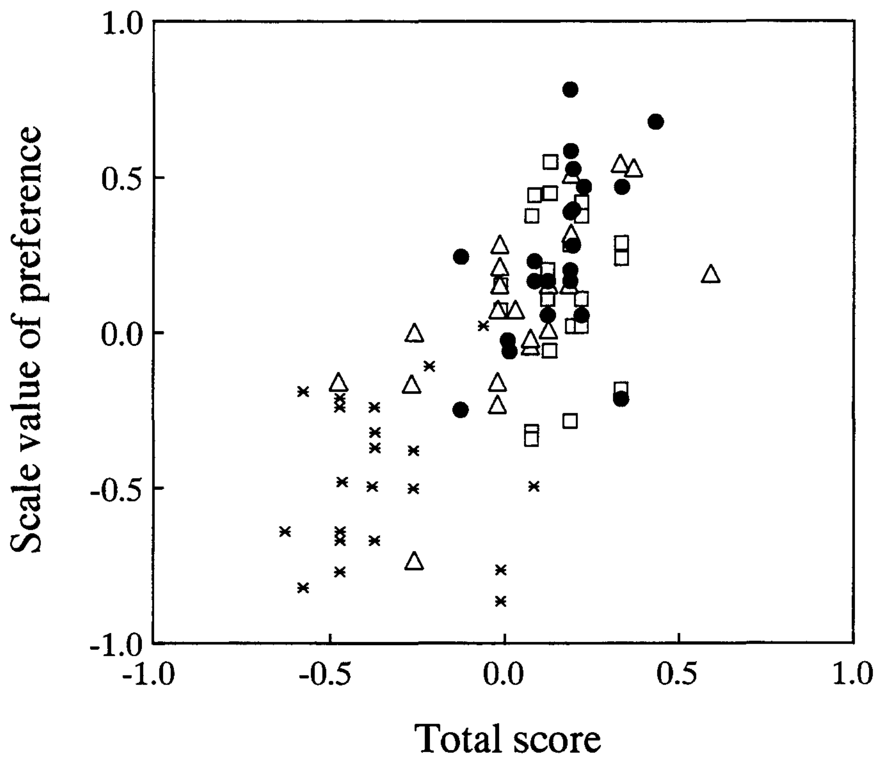


Figure 2.3. Relationship between scale values obtained by subjective judgements and total scores calculated by factor analysis using scores shown in Figure 4 (□ source 1, △ source 2, * source 3, ● source 4).

Table 2.1. Correlation coefficients between factors.

	SV	LL	Δt_1	IACC	τ_{IACC}
SV	1.000	0.171	-0.093	-0.008	0.541
LL	-	1.000	-0.037	-0.702	0.078
Δt_1	-	-	1.000	0.026	-0.036
IACC	-	-	-	1.000	-0.135
τ_{IACC}	-	-	-	-	1.000

2.6. Conclusions

In this study, the subjective preference of source locations on the stage is examined at each set of seats. The rear source (source 4) is more preferred than that of the other sources. The side source (source 3) indicates low preference, due to the interaural time delay of IACC. The initial time delay gap has a small influence on the total score.

This study introduces the effects of the interaural time delay of the IACC on the preference. If the IACC is obtained at a certain interaural time delay, then scores decrease rapidly. The results of the analysis described here demonstrate that the theory of calculating subjective preference by use of four physical parameters is supported only when the maximum value of interaural cross-correlation maintained at τ_{IACC} = 0. This condition is usually obtained in a real concert facing the visible performer.

Chapter 3

Apparent Source Width (ASW) in relation to the IACC and the Width of the Interaural Cross-correlation Function W_{IACC}

3.1. Introduction

As stated in section 1.2.1, the ASW is related to the spectral component of the source signal as well as the IACC. For example, even if the IACC is constant, the ASW increases as the center frequency of octave band noise become lower or as the lower frequency components increase. These facts are reflected in the interaural cross-correlation function. The peak of the function become broader as the center frequency of octave band noise become lower. Based on the cross-correlation mechanism in the auditory-brain model, it is proposed that these results may be described by factors included in the interaural cross-correlation function itself, namely, IACC and $W_{IACC}^{(0.1)}$ defined in section 1.4. The purpose of this chapter is to examine whether or not the ASW can be calculated as a function of both the IACC and the $W_{IACC}^{(0.1)}$.

To obtain a scale values of ASW, paired comparison tests were performed. In Experiment 1, the values of W_{IACC} were varied by changing the center frequencies of one-third-octave bandpass noises. In the test for one-third-octave band noise, the value of W_{IACC} is constant using one center frequency, even if the value of IACC is different. In this particular case, W_{IACC} can be replaced by the center frequency of the noise signal. However, W_{IACC} depends on the bandwidth of the bandpass noise signal also. Experiment 2 was conducted controlling the bandwidth using one center frequency. Experiment 3 was performed whether or not the formula described in above experiments may be applied to a music signal. To control of both the IACC and the W_{IACC}, the delay time of two reflections was changed here.

3.2. Subjective Judgment of ASW for Noise Signals

3.2.1. General procedure

Two symmetrical lateral reflections (±54°) added to the frontal direct sound (0°) were simulated in an anechoic chamber. The distances between the loudspeakers and the center on the subject's head were 0.90±0.01 m. To produce incoherent conditions, the time delays Δt_1 and Δt_2 between the direct sound and two reflections were fixed at 20 ms and 30 ms, respectively. The values of IACC were adjusted by controlling the sound pressure ratio of the reflections to the level of the direct sound. The listening level affects ASW (Keet, 1968) and, therefore, the total A-weighted sound levels at the ear canal entrances of all sound fields were kept constant at a peak of 75 dB. The interaural cross-correlation function was measured with 1/2-inch condenser type microphones placed at the entrance of the ears of a subject. The analog outputs from the microphones were passed through an A-weighting network and were digitized at a sampling frequency of 48 kHz. The interaural cross-correlation function was obtained from the whole spectrum cross-correlated without any band filter.

To obtain a scale value for ASW, paired-comparison tests were performed. The subjects were asked to judge which of two sound sources they perceived to be wider. The duration of each stimulus was 3 s and the silent interval between stimuli was 1 s. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order.

3.2.2. Experiment 1

A. Method

One-third-octave bandpass noises were used as a source signal. The center frequencies of the noise were 250 Hz, 500 Hz, 1 kHz, and 2 kHz. IACCs were set 0.90 and 0.70 for the center frequency of 250 Hz and 0.90, 0.70 and 0.40 for the center frequency of 500 Hz, 1 kHz and 2 kHz. The IACC = 0.40 for the center frequency of 250 Hz cannot realize in this condition. The values of IACC and $W_{IACC}^{(0.1)}$ were controlled by measuring the interaural cross-correlation function as listed in Table 3.1. The calculated values of $W_{IACC}^{(0.1)}$ by Equation (1.7) were close to the measured ones with an accuracy of ±0.02 ms.

Paired-comparison tests of eleven sound fields listed in Table 3.1 were conducted. The number of subjects was ten. The test consisted of 55 pairs (N(N-1)/2, N = 11) of stimuli, in total. The session was repeated five times, interchanging the order of each pair, for all subjects. It took about ten minutes for one session.

B. Results

Fifty responses (10 subjects x 5 repeats) to each sound field were obtained. Consistency tests indicate that all subjects have a significant ($p < 0.05$) ability to discriminate ASW. The test of agreement also indicates that there was significant ($p < 0.05$) agreement among all subjects. A scale value for ASW was obtained by applying the method, a modification of the Thurstone method (Ando and Singh, 1996) after averaging the results of 10 subjects.

Table 3.1. Values of IACC and $W_{IACC}^{(0.1)}$ controlled for sound fields in subjective judgement of ASW for one-third-octave bandpass noises.

One-third-octave center frequency	IACC	$W_{IACC}^{(0.1)}$ [ms]
250 Hz	0.90	0.55
	0.72	0.56
500 Hz	0.89	0.26
	0.69	0.26
	0.38	0.27
1 kHz	0.89	0.12
	0.69	0.12
	0.42	0.14
2 kHz	0.90	0.06
	0.70	0.06
	0.39	0.06

Table 3.2. Results of the two-way ANOVA for scale values of ASW using one-third-octave bandpass noises with the factors of IACC and $W_{IACC}^{(0.1)}$.

Factor	Sum of square	DF	Mean square	F-ratio
IACC	2.12	2	1.06	220.63**
$W_{IACC}^{(0.1)}$	2.62	3	0.87	181.67**
Residual	0.02	5	0.01	-

** p < 0.01.

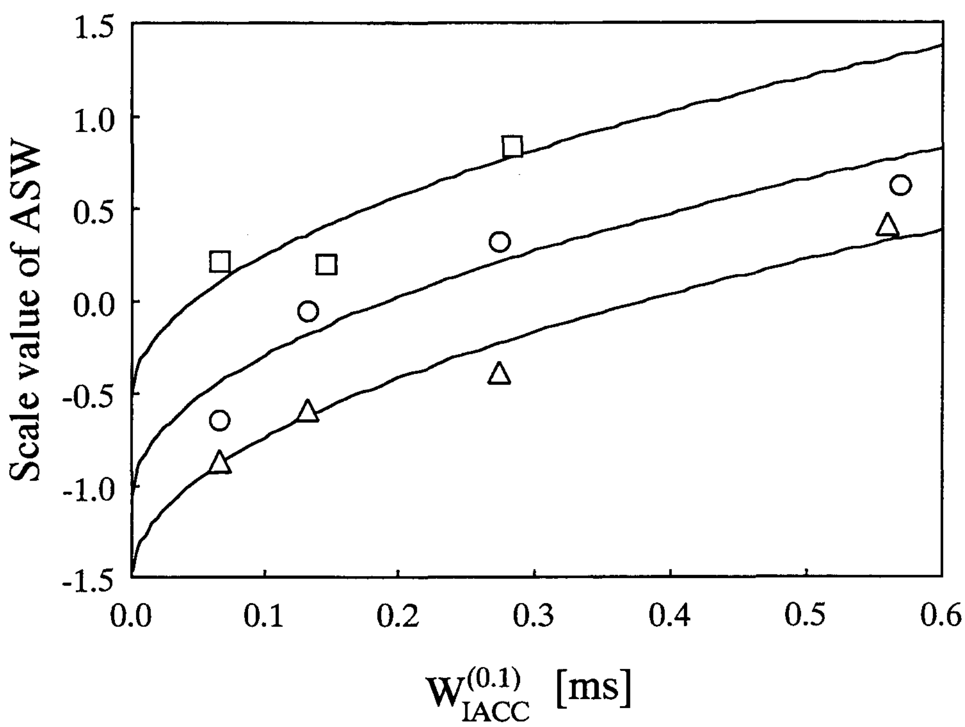


Figure 3.1. Average scale values of ASW for one-third-octave bandpass noises as a function of $W_{IACC}^{(0.1)}$ and as a parameter of IACC. △: IACC = 0.90; ○: IACC = 0.70; □: IACC = 0.40. The regression curve is expressed by Equation (3.2), $a \approx -1.64$ and $b \approx 2.44$.

The results of the analysis of variance for scale values of ASW are indicated in Table 3.2. It was found that the explanatory factors IACC and $W_{IACC}^{(0.1)}$ are significant ($p < 0.01$). The error term which includes the interaction term is small enough. This indicates that IACC and $W_{IACC}^{(0.1)}$ contribute to the scale value of ASW independently, which may be expressed by

$$s(ASW) \approx s(IACC) + s(W_{IACC}^{(0.1)}). \tag{3.1}$$

The scale value of ASW is formed by interpolation from a nonlinear equation such as

$$s(ASW) \approx a(IACC)^{3/2} + b(W_{IACC}^{(0.1)})^{1/2}, \tag{3.2}$$

where a and b are the coefficients to be evaluated. The values of the power, 3/2 and 1/2, for the terms of IACC and $W_{IACC}^{(0.1)}$ in Equation (3.2) are selected to give the best correlation between the scale values obtained by paired comparison tests and the scale values calculated by Equation (3.2). The scale value of preference and subjective diffuseness are also expressed in terms of the 3/2 power of the IACC (Ando and Kurihara, 1986; Singh, Kurihara, and Ando, 1994). Figure 3.1 shows the observed scale value of ASW for one-third-octave bandpass noises as a function of the $W_{IACC}^{(0.1)}$ and as a parameter of IACC. The curves in Figure 3.1 confirm the calculated scale value of Equation (3.2), $a \approx -1.64$ and $b \approx 2.44$. These coefficients were obtained by the multiple regression.

3.2.3. Experiment 2

A. Method

The bandpass noises of 500 Hz center frequency were used as a source signal. The bandwidths were one-third-octave width, one-octave width, two-octave width, and three-octave width. The values of IACC and $W_{IACC}^{(0.1)}$ were controlled by measuring the interaural cross-correlation function as listed in Table 3.3.

Paired-comparison tests of twelve sound fields listed in Table 3.3 were conducted. The number of subjects was four. The test consisted of 66 pairs (N(N-1)/2, N = 12) of stimuli in total. The session was repeated ten times, interchanging the order of each pair, for all subjects. It took about twelve minutes for one session.

Table 3.3. Values of IACC and $W_{IACC}^{(0.1)}$ controlled for sound fields in subjective judgement of ASW for bandpass noise of 500 Hz center frequency.

Bandwidth	IACC	$W_{IACC}^{(0.1)}$ [ms]
1/3 octave	0.83	0.28
	0.67	0.28
	0.51	0.28
1/1 octave	0.84	0.24
	0.65	0.24
	0.51	0.24
2 octave	0.83	0.19
	0.65	0.19
	0.51	0.20
3 octave	0.84	0.15
	0.65	0.16
	0.51	0.16

B. Results

Forty responses (4 subjects x 10 times) to each sound field were obtained. Consistency tests indicate that all subjects have a significant ($p < 0.05$) ability to discriminate ASW. The test of agreement also indicates that there was significant ($p < 0.05$) agreement among all subjects. A scale value for ASW was obtained by applying the method, a modification of the Thurstone method (Ando and Singh, 1996).

Table 3.4. Results of the two-way ANOVA for scale values of ASW using bandpass noises of 500 Hz center frequency with the factors of IACC and $W_{IACC}^{(0.1)}$.

Factor	Sum of square	DF	Mean square	F-ratio
IACC	3.14	2	1.57	291.77**
$W_{IACC}^{(0.1)}$	0.59	3	0.20	36.54**
Residual	0.03	6	0.01	-

** $p < 0.01$.

The results of the analysis of variance for scale values of ASW are indicated in Table 3.4. It was found that the explanatory factors IACC and $W_{IACC}^{(0.1)}$ are significant ($p < 0.01$) for both signals. The error term which includes the interaction term is small enough. The values of the power, 3/2 and 1/2, for the terms of IACC and $W_{IACC}^{(0.1)}$ in Equation (3.2) also give the best correlation between the measured and calculated scale values. Figure 3.2 shows the observed scale value of ASW for bandpass noises of 500 Hz center frequency as a function of the $W_{IACC}^{(0.1)}$ and as a parameter of IACC. The curves in Figure 3.2 confirm the calculated scale value of Equation (3.2), $a \approx -3.26$ and $b \approx 3.55$. These coefficients were obtained by the multiple regression.

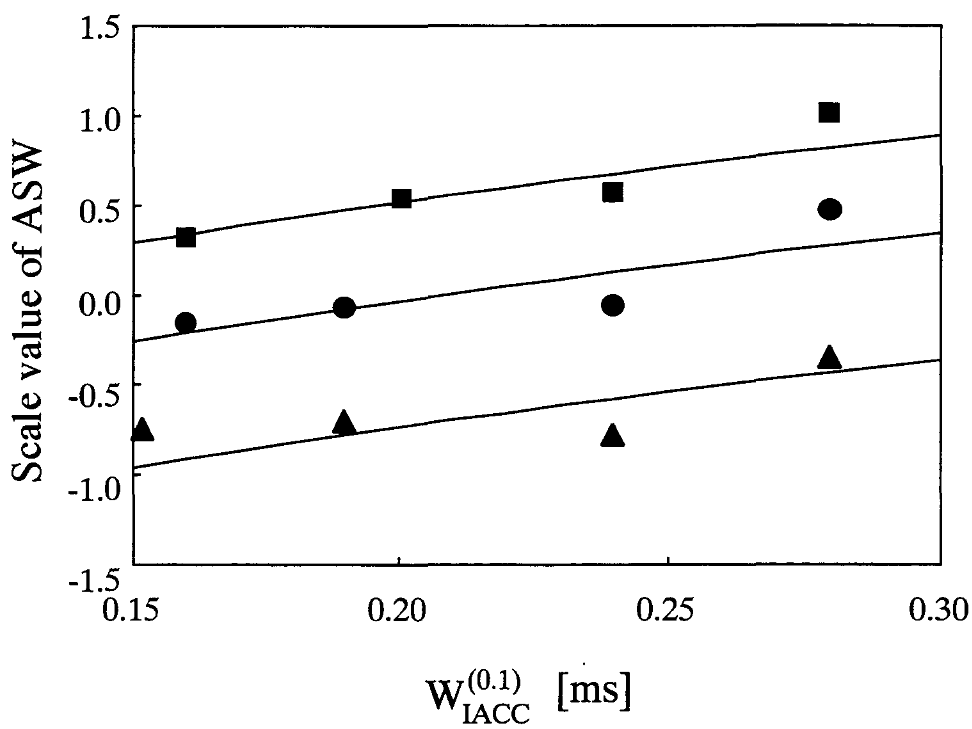


Figure 3.2. Average scale values of ASW for the bandpass noises of 500 Hz center frequency as a function of $W_{IACC}^{(0.1)}$ and as a parameter of IACC. ▲: IACC = 0.82; ●: IACC = 0.65; ■: IACC = 0.51. The regression curve is expressed by Equation (3.2), $a \approx -3.26$ and $b \approx 3.55$.

3.2.4 Discussion

The coefficients a and b in Equation (3.2) were obtained by the multiple regression of the results from both experiment, and are listed in Table 3.5. Figure 3.3 shows the relationship between the measured scale values of ASW and the scale values of ASW calculated by Equation (3.2) with the coefficients a and b listed in Table 3.5. The correlation coefficient between the measured and calculated scale values is 0.92 ($p < 0.01$). Calculated scale values of ASW by Equation (3.2) with the coefficients listed in Table 3.5 are close to the measured scale values of ASW.

Table 3.5. Coefficients a and b in Equation (3.2) with 95 percent reliability and the maximum error.

a	b	95 percent reliability	Maximum error
-2.14	2.60	± 0.10	± 0.47

Coefficients a and b in Equation (3.2) for each individual are calculated by a multiple regression analysis and are listed in Table 3.6. Figure 3.4 shows the relationship between the measured scale value of ASW obtained from the experiment and the calculated scale values of ASW by Equation (3.2). The different symbols indicate values obtained with the different subjects. Differences between the measured scale values and the calculated scale values, except for only two data, have the range of ±0.67 which corresponds to a probability of 75 percent, and is thus less than the value of distinction. The correlation coefficient between the calculated scale values of ASW and the measured scale values of ASW is 0.91 ($p<0.01$). The ASW for each individual can be calculated by the same equation to calculating the global ASW, simply by changing the weighting coefficients a and b.

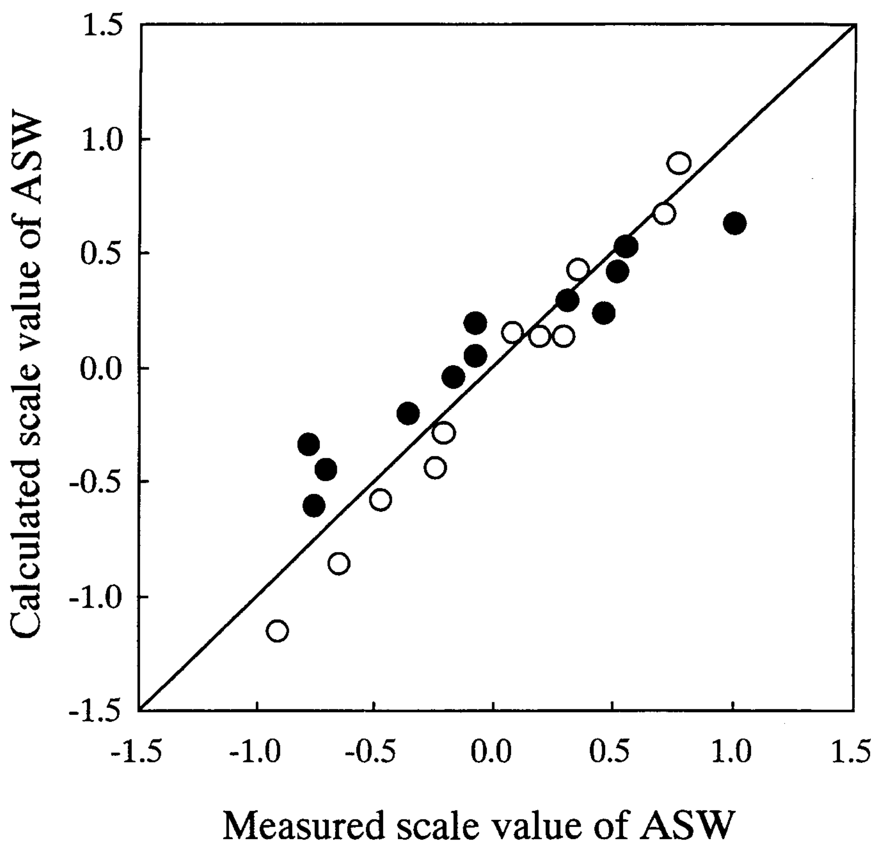


Figure 3.3. Relationship between the measured scale values of ASW and scale values of ASW calculated by Equation (3.2) with the coefficients a and b for the noise signals listed in Table 3.5. ○: One-third-octave bandpass noises; ●: Bandpass noises of 500 Hz center frequency. The correlation coefficient, $r = 0.93$ ($p < 0.01$).

Table 3.6. Coefficients a and b in Equation (3.2) for each individual using (a) one-third-octave bandpass noises and (b) bandpass noises of 500 Hz center frequency, together with the correlation coefficients between the measured scale values of ASW and the calculated scale values of ASW by Equation (3.2); the 95 percent reliability; and the maximum error.

(a) One-third-octave bandpass noises

Subject	a	b	Correlation coefficient	95 percent reliability	Maximum error
SH	-1.21	2.58	0.88	±0.18	±0.46
TS	-1.50	3.18	0.97	±0.12	±0.27
CC	-1.05	2.82	0.97	±0.10	±0.21
SY	-0.94	2.92	0.91	±0.17	±0.56
MK	-2.21	2.09	0.92	±0.17	±0.42
ST	-2.57	1.94	0.94	±0.16	±0.54
TH	-2.04	1.32	0.87	±0.19	±0.59
FK	-0.99	3.27	0.89	±0.20	±0.52
NK	-1.79	2.14	0.80	±0.23	±0.78
OS	-2.09	2.14	0.94	±0.15	±0.40

(b) Bandpass noises of 500 Hz center frequency

Subject	a	b	Correlation coefficient	95 percent reliability	Maximum error
SS	-3.60	4.27	0.92	±0.20	±0.57
AJ	-3.40	3.97	0.92	±0.18	±0.41
FK	-3.43	4.03	0.95	±0.14	±0.39
OK	-2.49	2.89	0.87	±0.26	±0.52

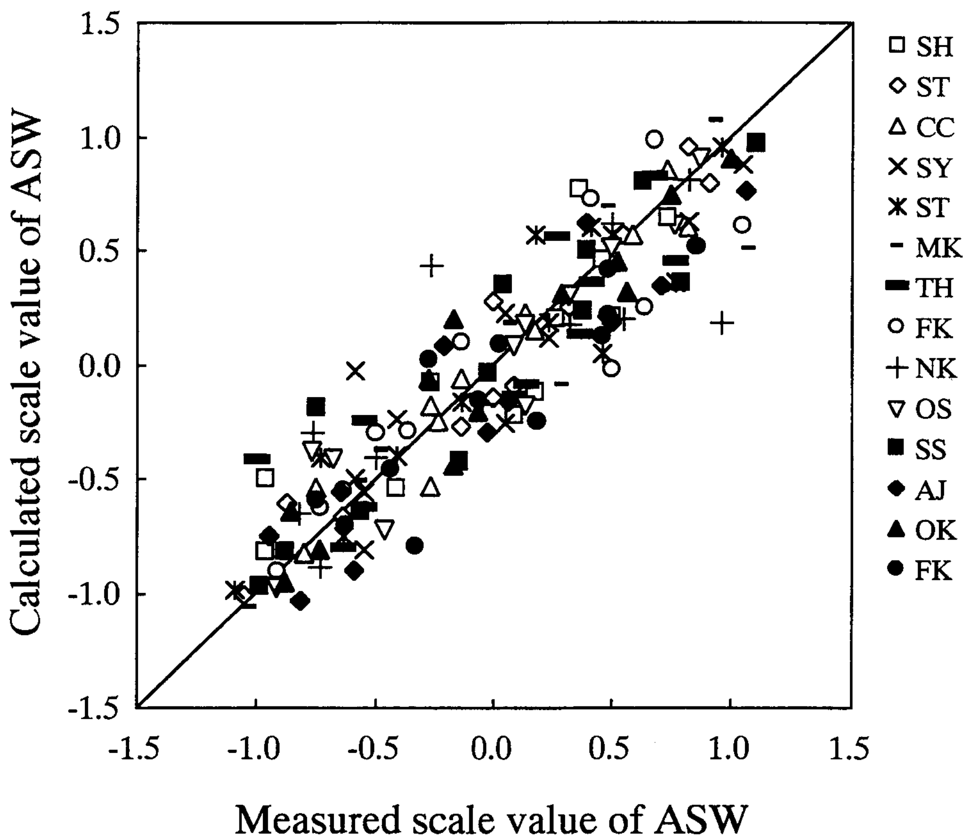


Figure 3.4. Relationship between the measured individual scale values of ASW for noise signals and scale values of ASW calculated by Equation (3.2) for each individual. The correlation coefficient, $r = 0.91$ ($p < 0.01$).

3.3 Application for Music Signal

3.3.1 Experiment 3

A. Method

Music motif A (Royal Pavane by Gibbons; Ando, 1985) was used as a source signal. In order to control of both the IACC and the W_{IACC}, the delay time of two reflections relative to the direct sound was changed. In the sound field under the incoherent condition, the values of W_{IACC} are constant using one center frequency, even if the value of IACC is different. When the delay time of the reflection approaches zero, the measured values of IACC increase since there is high coherence between the direct sound and reflection (Ando, 1977). The amplitude of reflections relative to the direct sound is -3 dB. The delay time of first reflection relative to the direct sound is controlled in the range of 1.0-3.0 ms. The delay times between two reflections are fixed following two conditions:

Table 3.7. Values of IACC and $W_{IACC}^{(0.1)}$ controlled for sound fields in subjective judgement of ASW for music motif A.

Delay time between two reflections [ms]	Δt_1 [ms]	IACC	$W_{IACC}^{(0.1)}$ [ms]
	1.7	0.94	0.26
0.0	1.9	0.93	0.30
	2.2	0.96	0.21
	1.9	0.54	0.30
1.0	2.2	0.55	0.23
	2.4	0.56	0.21

(1) there is no delay between two reflections; and

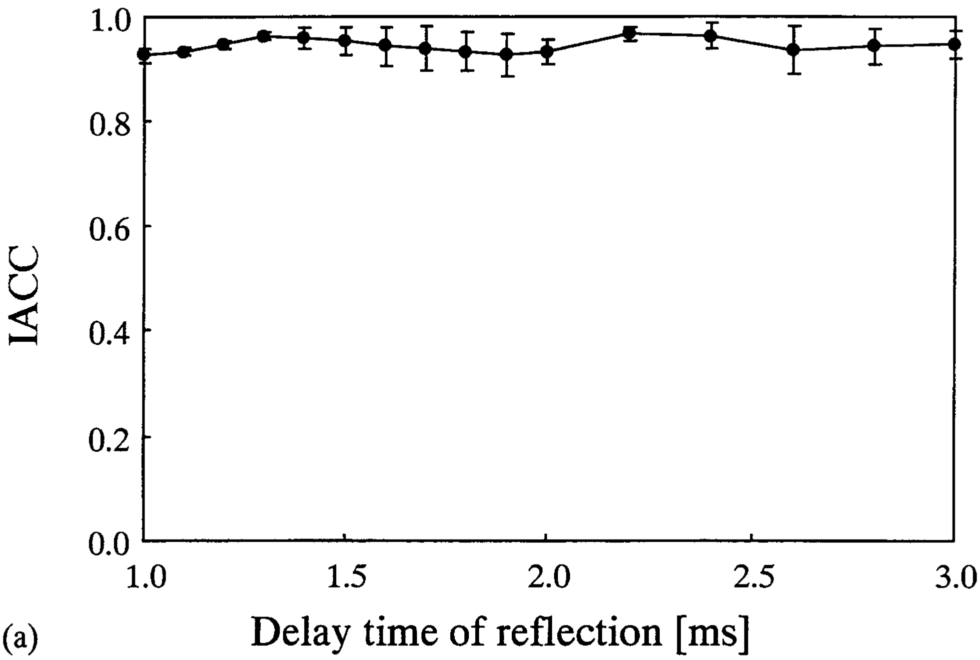
(2) the delay time between two reflections is 1 ms.

The interaural cross-correlation functions were measured using three subjects. The measured values of IACC and $W_{IACC}^{(0.1)}$ with 95 percent reliability were shown in Figures 3.5 and 3.6. The values of IACC were almost constant, and the values of $W_{IACC}^{(0.1)}$ were changed.

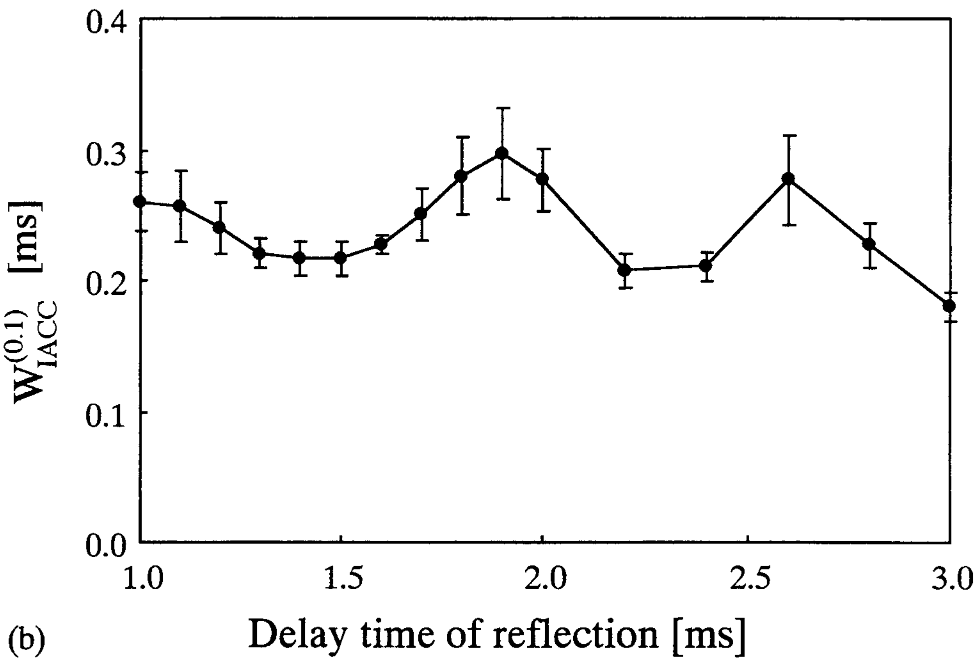
Paired-comparison tests of six sound fields listed in Table 3.6 were conducted. The number of subjects was four. The test consisted of 15 pairs (N(N-1)/2, N = 6) of stimuli in total. The signal duration of each stimulus was 5 s and the silent interval between stimuli was 1 s. The test was repeated ten times interchanging the order of each pair, for all subjects.

B. Results

Forty responses (4 subjects x 10 times) to each sound field were obtained. The scale value of ASW was obtained by applying the method proposed by Ando and Singh here also. Consistency tests indicate that three subjects have a significant ($p < 0.05$) ability to discriminate ASW. The test of agreement indicates that there was significant ($p < 0.01$) agreement among all of them.



(a)



(b)

Figure 3.5. Measured values of IACC and $W_{IACC}^{(0.1)}$ for music motif A with 95 percent reliability as a function of the delay time of the reflection. There is no delay between two reflections: (a) IACC; and (b) $W_{IACC}^{(0.1)}$.

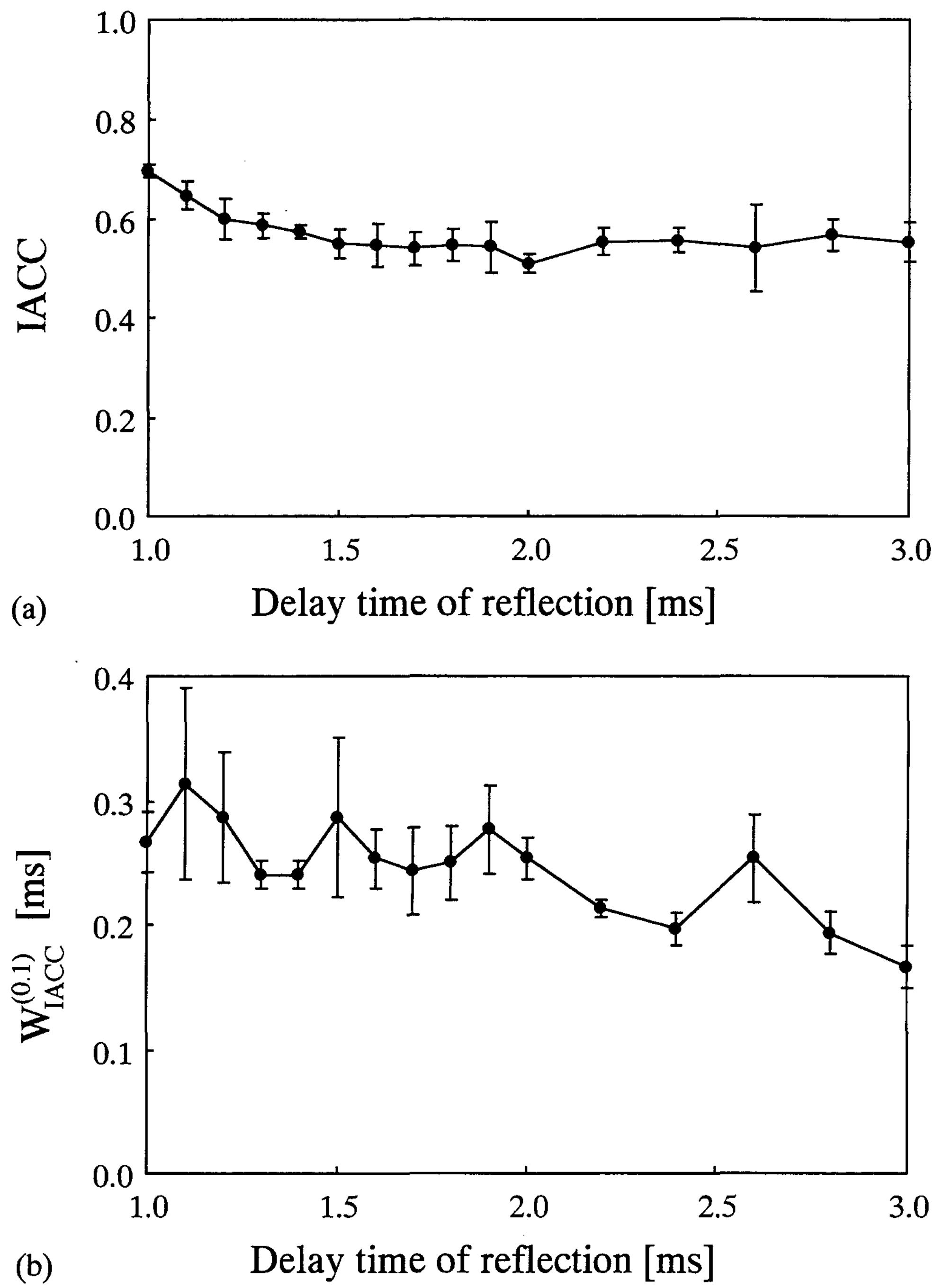


Figure 3.6. Measured values of IACC and $W_{IACC}^{(0.1)}$ for music motif A with 95 percent reliability as a function of the delay time of the reflection. The delay time between two reflections is 1 ms: (a) IACC; and (b) $W_{IACC}^{(0.1)}$.

Table 3.8. Results of the two-way ANOVA for scale values of ASW using music motif A with the factors of IACC and $W_{IACC}^{(0.1)}$.

Factor	Sum of square	DF	Mean square	F-ratio
IACC	6.35	1	6.35	155.84**
$W_{IACC}^{(0.1)}$	0.11	2	0.00	0.08
IACC* $W_{IACC}^{(0.1)}$	0.14	2	0.07	1.77
Residual	0.49	12	0.04	-

** $p < 0.01$.

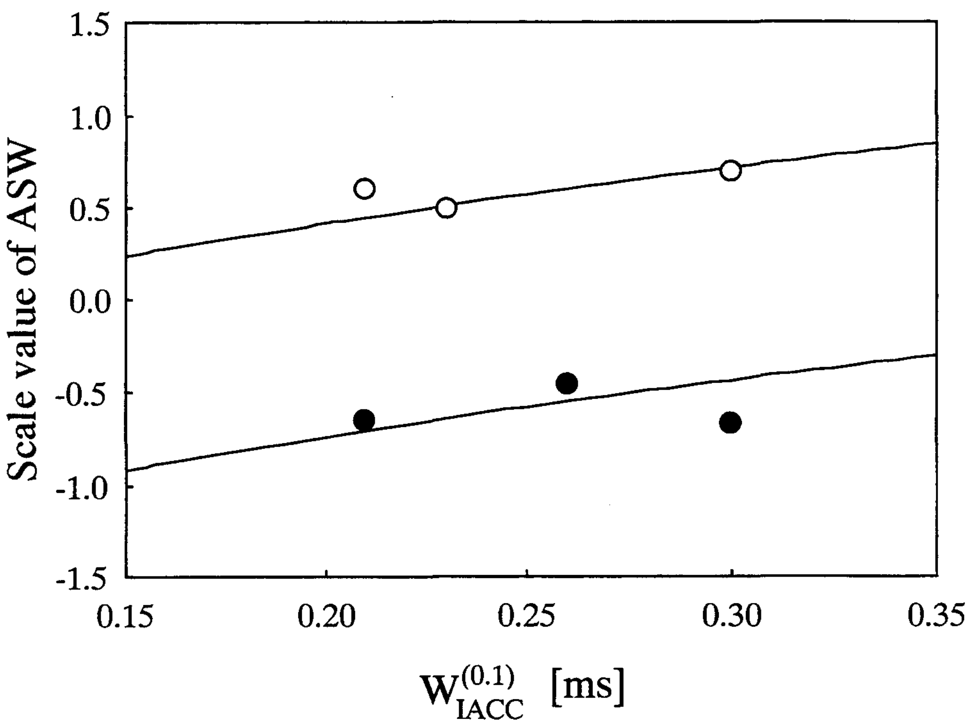


Figure 3.7. Average scale values of ASW for music motif A as a function of $W_{IACC}^{(0.1)}$ and as a parameter of IACC. ●: IACC = 0.94; ○: IACC = 0.55. The regression curve is expressed by Equation (3.2) with the coefficients a and b are for the noise signals listed in Table 3.5.

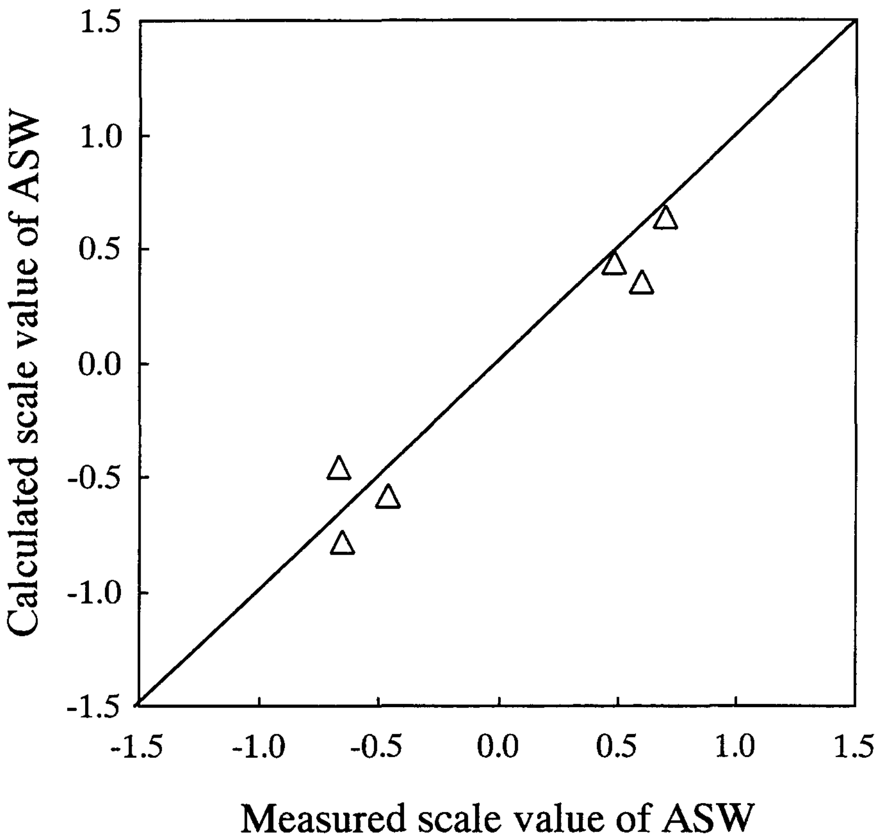


Figure 3.8. Relationship between the measured scale values of ASW for music signal and scale values of ASW calculated by Equation (3.2) with the coefficients a and b are for the noise signals listed in Table 3.5. The correlation coefficient, $r = 0.97$ ($p < 0.01$)

The results of the analysis of variance for scale values of ASW are indicated in Table 3.7. It was found that the explanatory factor IACC is significant ($p < 0.01$) differences to a high degree. The factor $W_{IACC}^{(0.1)}$ is not significant since the difference of $W_{IACC}^{(0.1)}$ is small compared with that for one-third-octave bandpass noises. The interaction term between the factors of IACC and $W_{IACC}^{(0.1)}$ also is not significant.

Figure 3.7 shows the scale value of ASW as a function of $W_{IACC}^{(0.1)}$ and as a parameter of IACC. The curves show the calculated scale value by Equation (3.2) using the coefficients for noise signals listed in Table 3.5.

3.3.2. Discussion

For an application for music signal of Equation (3.2), it is remarkable that calculated scale values of ASW agree well with measured scale values as shown in Figure 3.8. The correlation coefficient between the calculated and measured scale values is 0.92 ($p < 0.01$). Calculated scale values of ASW using the coefficients a and b for noise signals listed in Table 3.4 may be applied for scale values of ASW for music signals. The scale values obtained in different test series with different source signals agree with each other.

3.4. Conclusions

To calculate the ASW from the interaural cross-correlation function based on the cross-correlation mechanism of auditory pathways for spatial information, W_{IACC} is introduced in addition to IACC. The factor $W_{IACC}^{(0.1)}$ is defined by the time interval of the interaural cross-correlation function between the values of ten percent below the IACC. The scale value of ASW for one-third-octave bandpass noises and the bandpass noises of 500 Hz center frequency obtained by paired-comparison tests can be described by two dimensional factors: IACC and W_{IACC}. The ASW may be formulated by superposition of two terms the 3/2 power of IACC and the 1/2 power of $W_{IACC}^{(0.1)}$. The scale value of ASW for a music signal is also described by the same equation for noise signals.

Chapter 4

Preferred Delay Time of a Single Reflection for Cellists in relation to the Autocorrelation Function of the Source Signals

4.1. Introduction

In order to make an excellent concert hall, we need to design the sound fields not only in the audience area but also in the stage area for performers. The primary issue is that the stage enclosure should be designed to provide a sound field in which performers can play easily.

From the previous studies, it is found that the most preferred conditions of the temporal factors for listeners can be described in relation to the effective duration of the long-time autocorrelation function of the source signal (Ando, 1985). When music signal contains a large fluctuation in tempo, it is more accurately expressed by the minimum value of the effective duration of the running autocorrelation function (Andoet al., 1989). Nakayama (1984) showed that the preferred delay time of a single reflection for alto-recorder soloists can be also determined from the duration of the long-time autocorrelation function of the source signal. The present study examined whether or not the preferred delay time of a single reflection for each cello soloist can be calculated from the amplitude of the reflection and the minimum value of the effective duration of the running autocorrelation function of the music motifs played by that cellist. The scale values of preference for the delay time of a single reflection were obtained using a paired comparison method, and the results were compared with those for the alto-recorder players and listeners.

4.2. Experiment

4.2.1. Music motifs

Music motifs were characterized in terms of the running autocorrelation function of the source signal played. The same music motifs (motifs I and II) used in the experiments conducted by Nakayama (1984) were used here also. The tempo of motif I was faster than that of motif II as shown in Figure 4.1. The two music motifs played by each of five cellists were picked up by a microphone in front of the cellist. The distance between the microphone and the center of the cello body was 0.50 ± 0.01 cm. The music tempo was maintained with the help of a visual (silent) metronome. Each music motif was played three times by each cellist. The minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of a music signal is the most active part of the music signal, containing important information and influencing the subjective attributes related to the temporal factors (Ando et al., 1989). The values of the effective duration of the running autocorrelation functions of the music signals, after passing through an A-weighted network, were calculated. The running integration interval of autocorrelation function 2T was 2.0 s. This interval was chosen according to the results of several previous investigations (Ando et al., 1989; and Taguti, and Ando, 1997). Examples of effective duration of the running autocorrelation function for music motif I played by subjects B and E are shown in Figure 4.2. The minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function for each cellist and each session are listed in Table 4.1. For all cellists, the minimum values of the effective duration $(\tau_e)_{min}$ for music motif I were shorter than those for music motif II. Mean values of $(\tau_e)_{min}$ were 46 ms for music motif I and 84 ms for music motif II, and for both motifs the ranges of $(\tau_e)_{min}$ are within ±5 ms. Individual differences in the values of the effective duration of the running autocorrelation function may depend on the performer's style.

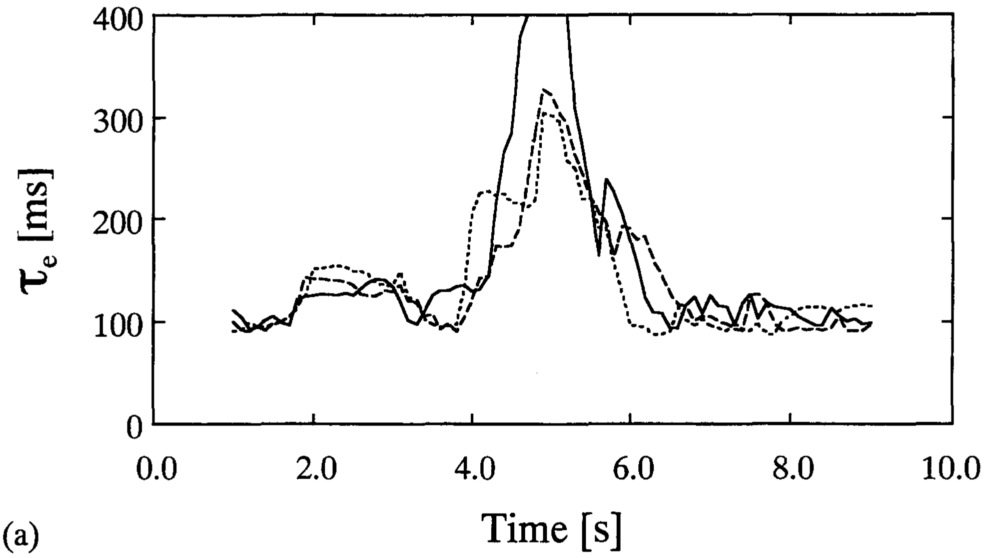
4.2.2. Procedure

The single reflection from the back wall in the stage enclosure was simulated in an anechoic chamber by a loudspeaker 0.80±0.01 m from the head of the cellist. The sound signal was picked up by a 1/2-inch condenser type microphone at the entrance of the performer's left ear and was reproduced by the loudspeaker after passing through a digital delay machine. The amplitudes of reflection A_1, relative to that of the direct sound measured at the entrance of the performer's left ear, were kept constants at -15 dB and -21 dB when the cellist played a musical note 'a' (442 Hz).

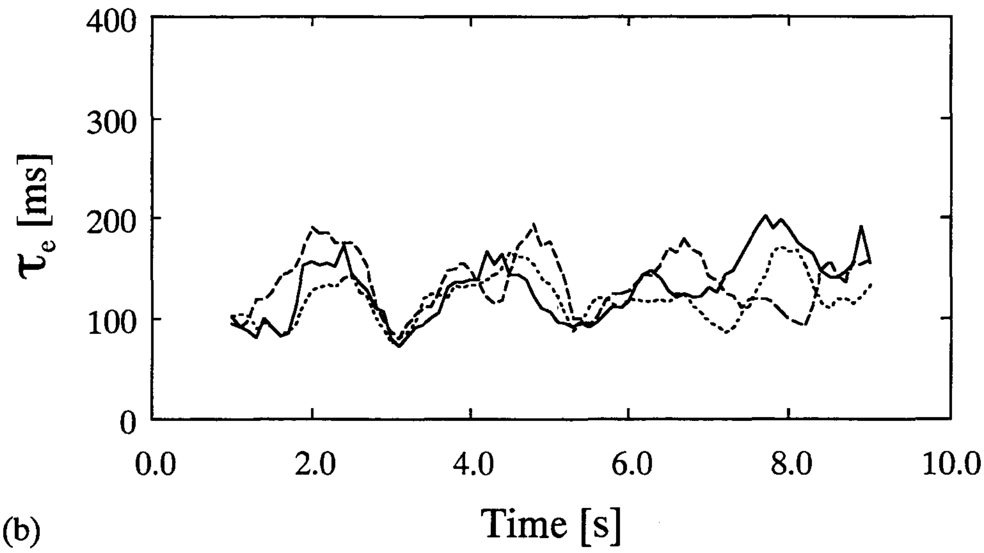
Music Motif I

Music Motif II

Figure 4.1. Music scores of motifs I and II composed by Tsuneko Okamoto (Nakayama, 1984).



(a)



(b)

Figure 4.2. Examples of the measured effective duration of the running autocorrelation function with a 100 ms interval as a function of the time. Each music motif was played three times by each cellist: (a) Music motif I for subject B, $(\tau_e)_{min}$ = 50±2 ms; and (b) Music motif I for subject E, $(\tau_e)_{min}$ = 37±1 ms.

Table 4.1. Minimum values of running τ_e of autocorrelation function for music motif played by each cellist.

Subject	Session	Music motif I [ms]	Music motif II [ms]
A	1st	35	90
	2nd	41	96
	3rd	41	89
B	1st	52	92
	2nd	49	87
	3rd	49	89
C	1st	37	89
	2nd	38	86
	3rd	36	93
D	1st	57	87
	2nd	56	85
	3rd	54	86
E	1st	37	71
	2nd	38	74
	3rd	36	79
Averaged		46	84

Table 4.2. Range of delay times of reflection varied due to the $(\tau_e)_{min}$ of each cellist in subjective preference judgments.

Music	A_1 [dB]	Values of delay times of reflection [ms]				
Motif I	-15	11.8±0.8	24.0±2.0	48.0±4.0	72.0±6.0	96.0±8.0
	-21	15.6±4.4	33.6±7.4	67.2±6.0	100.8±22.2	134.4±29.6
Motif II	-15	19.4±2.6	39.4±5.6	78.8±11.2	118.2±16.8	157.6±22.4
	-21	23.6±3.4	47.8±7.2	95.6±14.4	143.4±21.6	191.2±28.8

4.2.3. Paired comparison tests

Paired comparison tests were conducted for the five sound fields listed in Table 4.2. The delay times of the reflection differed between cellists according to the $(\tau_e)_{min}$ of the running autocorrelation function obtained in advance since the preferred delay time of a single reflection is determined from the $(\tau_e)_{min}$ of the running autocorrelation function of source signal. The five subjects were asked to decide which of two sound fields would be easier for them to perform in. The test consisted of 10 pairs (N(N-1)/2, N = 5) of stimuli in total, and for all subjects the test was repeated three times interchanging the order of the pairs. It took about 20 minutes for each cellist and for each music motif.

4.3. Results and Discussion

Fifteen responses (5 subjects x 3 repeats) to each sound field were obtained and were confirmed by consistency tests. The scale values of preference for each cellist were obtained by applying the method that Ando and Singh proposed for modifying the Thurstone method.

Figure 4.3 shows an example of the regression curve for the scale value of preference and the method of estimating the most preferred delay time $[\Delta t_1]_p$. The peak of this curve denotes the most-preferred delay time. The most-preferred delay times for individual cellists and the global preference results are listed in Table 4.3. Global and individual results (except for that of subject E) for music motif II were longer than those for music motif I.

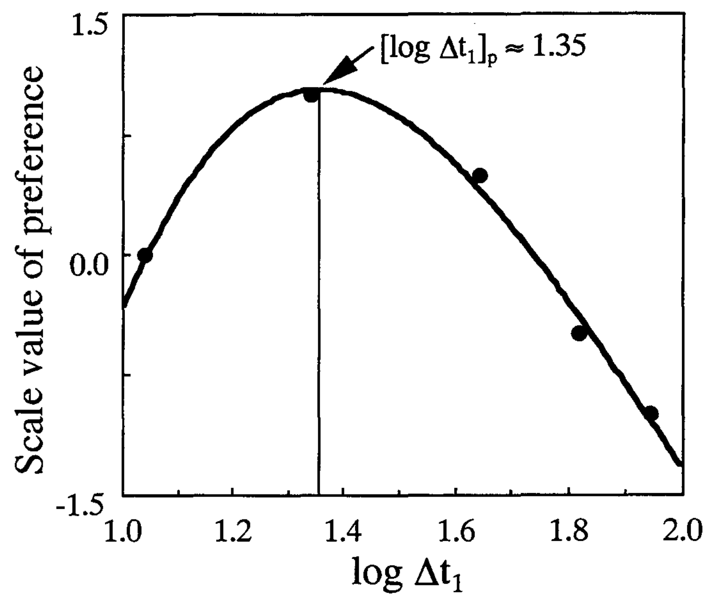


Figure 4.3. Example of the regression curve for the preferred delay time (Subject D, Music motif I, -15dB). $[\log \Delta t_1]_p \approx 1.35$, thus $[\Delta t_1]_p \approx 22.6$ [ms].

Table 4.3. Judged and calculated preferred delay times of a single reflection for cello soloists. Calculated values of $[\Delta t_1]_p$ are obtained by Equation (4.3) using the amplitude of the reflection A_1, and $(\tau_e)_{min}$ for music signal performed by each cellist.

A_1 [dB]	A'_1 [dB] $(=A_1+10)$	A'_1	Cellist	Judged $[\Delta t_1]_p$ [ms] Motif I	Judged $[\Delta t_1]_p$ [ms] Motif II	Calculated $[\Delta t_1]_p$ [ms] Motif I	Calculated $[\Delta t_1]_p$ [ms] Motif II
			A	16.2	47.9	16.3	38.5
			B	< 12.0	73.8	35.2	62.7
-15	-5	0.56	C	< 12.0	60.8	21.3	51.3
			D	22.6	38.2	35.1	53.9
			E	17.6	63.6	17.3	35.2
			Global	18.0	48.3	24.3	47.5
			A	18.1	48.4	21.8	51.5
			B	61.2	105.0	59.3	105.6
-21	-11	0.28	C	---	77.9	---	80.6
			D	74.6	86.8	56.9	87.4
			E	< 14.0	42.2	24.8	50.2
			Global	30.4	71.8	37.6	73.4

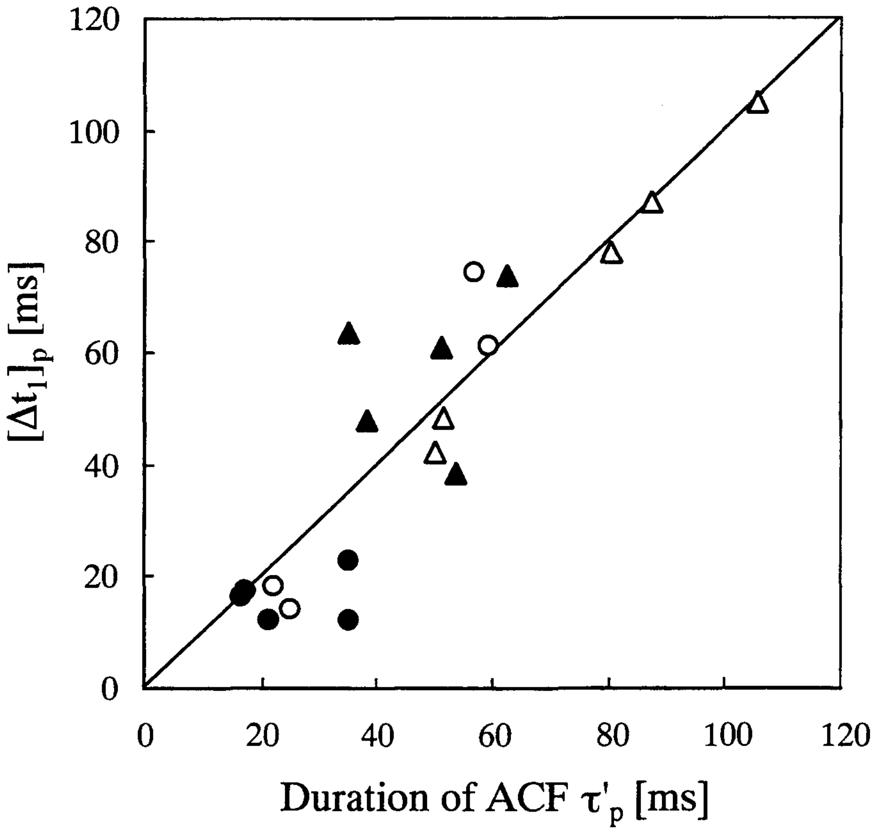


Figure 4.4. Relationship between the most preferred delay time $[\Delta t_1]_p$ and the duration τ'_p of the autocorrelation function calculated by equation (4.3). The correlation coefficient, r = 0.91 (p < 0.01). ●: Music motif I, -15 dB; ○: Music motif I, -21 dB; ▲: Music motif II, -15 dB; △: Music motif II, -21 dB.

Table 4.4. Coefficients c for individual and global results, when $k = 1/2$.

	Cellist					Averaged
	A	B	C	D	E	(Global)
c	0.47	1.61	1.10	1.30	0.67	≈ 1

The most-preferred delay time of a single reflection is described by the duration τ'_p of the autocorrelation function, which is expressed by

$$[\Delta t_1]_p = \tau'_p \tag{4.1}$$

such that

$$|\phi_p(\tau)|_{envelope} \approx kA'^c_1 \quad \text{at} \quad \tau = \tau'_p, \tag{4.2}$$

The values k and c are constants that depend on the subjective attributes (Ando, 1998). The value of A'_1 is the amplitude of the reflection being defined by $A'_1 = 1$ relative to -10 dB of the direct sound as measured at the ear's entrance. This is due to the over-estimation of the reflection by the performer (Nakayama, 1984). If the envelope of the autocorrelation function is exponential, Equation (4.2) simply yields

$$\tau'_p = (\log_{10}\frac{1}{k} - c\log_{10}A'_1)\tau_e. \tag{4.3}$$

According to a previous study (Ando et al., 1989), the effective duration τ_e of the long-time autocorrelation function in Equation (4.3) is replaced by the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of music used for judgments. Using the Quasi-Newton method, we obtain $k \approx 1/2$ and $c \approx 1$.

It is worth noting that the coefficients k and c for alto-recorder soloists were respectively 2/3 and 1/4 and for listeners were respectively 0.1 and 1. After setting $k = 1/2$, we obtained the coefficient c for each individual as listed in Table 4.4. The average value for the five cellists was 1.06. This value corresponds to the global results. The relation between the most-preferred delay time $[\Delta t_1]_p$ obtained by preference judgment and the duration τ'_p of the autocorrelation function calculated by Equation (4.3) using $(\tau_e)_{min}$ is shown in Figure 4.4. Different symbols indicate the values obtained in different test series. The correlation coefficient is 0.91 ($p < 0.01$). The scale values of preference for each of the five cellists as a function of the delay time of a single reflection normalized by the calculated $[\Delta t_1]_p$ are shown in Figure 4.5. Different symbols indicate the scale values obtained in different test series. Each symbol has 25 data (5 subjects x 5 sound fields) except for the amplitude of -15 dB for music motif I (for which there were 20 data because consistency tests did not indicate a significant ability to discriminate preference in the results of Subject C). The scale values obtained in different test series are consistent with each other. The regression curve is expressed by (Ando, 1998)

$$S \approx -\alpha |x|^{3/2}, \tag{4.4}$$

where $x = \log \Delta t_1 / [\Delta t_1]_p$ and the weighting coefficient α is 2.3 for $x \geq 0$ and 1.0 for $x < 0$.

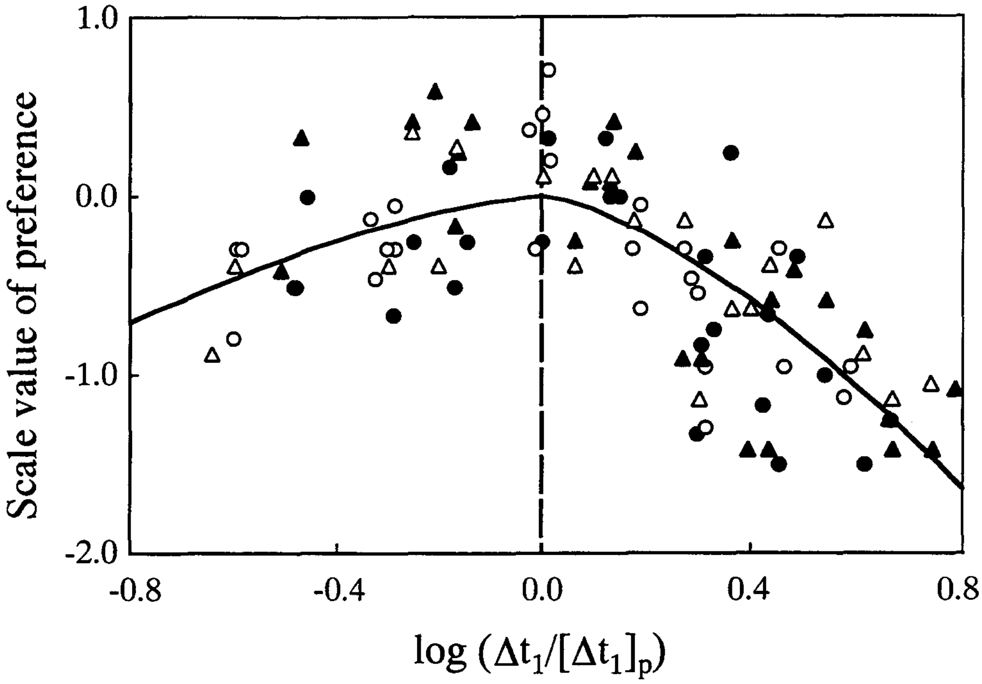


Figure 4.5. Scale values of preference for each of five cellists as a function of the delay time of a single reflection normalized by its most preferred delay time calculated by equation (4.3). ●: Music motif I, -15 dB; ○: Music motif I, -21 dB; ▲: Music motif II, -15 dB; △: Music motif II, -21 dB. The regression curve is expressed by equation (4.4).

Figure 4.6 shows a cello soloist's preferred delay time normalized by the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function as well as several subjective responses as a function of the normalized delay time of reflection calculated using the value of the effective duration τ_e of the long-time autocorrelation function of the source signal (Ando, 1998). These values can be calculated by Equation (4.3) with constants k and c for each subjective response. The alto-recorder soloist's preference is also plotted in this figure. The values for performers are close to the threshold of perception (aWs) for listeners.

Table 4.5. Optimum distance between the performer and the reflector calculated from Equation (4.4) in relation to the value of $(\tau_e)_{min}$ for the music signal played.

$(\tau_e)_{min}$ of the music signal [ms]	Distance of the reflector [m]						
	Cello soloist						Alto-recorder soloist
	A	B	C	D	E	Averaged	
30	3	10	6	8	4	6	2
50	6	21	13	16	8	13	4
70	9	(33)	21	(26)	13	20	6
90	13	(46)	(30)	(36)	18	(29)	8

Note: the value of τ_e for alto-recorder soloist was obtained for a long time autocorrelation function (2T = 32 s).

As an application, the delay time of a reflection can be controlled by adjusting the height of the reflectors above the stage. As listed in Table 4.5, the optimum distance between the performer and the reflector above the stage in relation to the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of the music program to be performed can be calculated. Here it is assumed that the distance between the instruments and the ear of the performer is 0.6 m for a cello soloist and 0.2 m for an alto-recorder soloist. The height of the reflector above the stage can be adjusted if the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of the music to be played is measured before the concert. For practical convenience, this adjustment may be made in the real sound field with the subsequent reverberation when the amplitude of a single reflection is replaced by the total amplitude of the reflections.

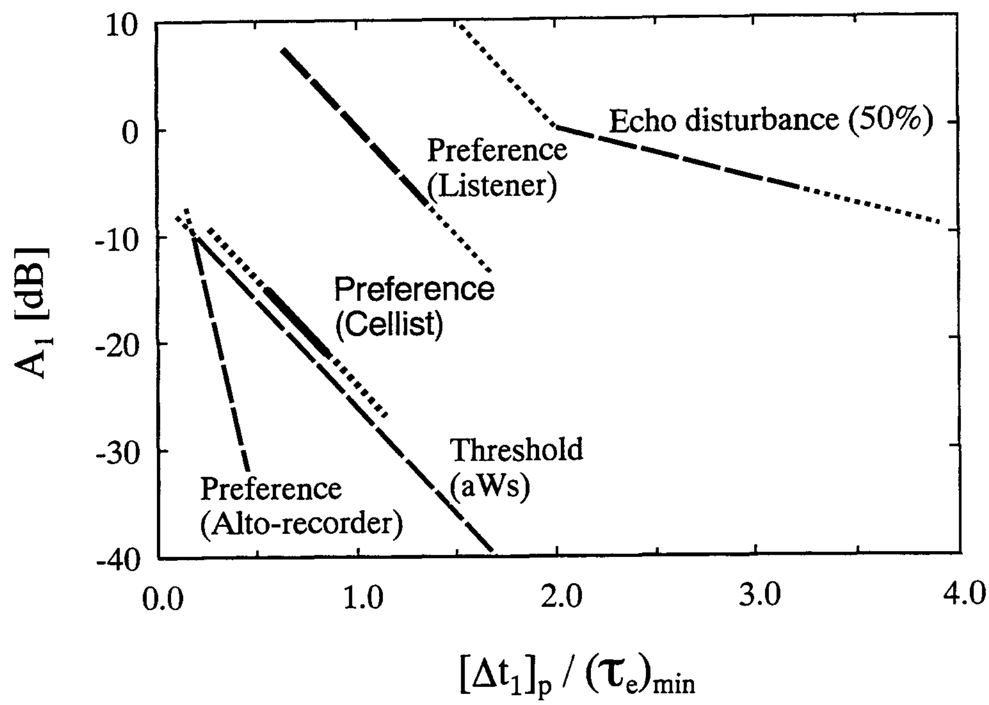


Figure 4.6. Averaged preferred delay time normalized by $(\tau_e)_{min}$ for cello-soloists, as well as several subjective responses as a function of the normalized delay time of reflection calculated by use of the value of τ_e of source signal (Ando, 1998).

4.4. Conclusions

The most-preferred delay time of a single reflection for each cellist can be calculated from the amplitude of the reflection and the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of the music motifs played by each cellist. The scale values of preference for both individual cellists and for global cellists with regard to the delay time of a single reflection can be expressed by a simple formula, normalizing the delay time by the most-preferred delay time observed for different music motifs.

Chapter 5

Summary and Conclusions

5.1. Summary and Conclusions of This Study

To produce an excellent sound field in a concert hall, it is necessary to find the significant physical factors on the subjective attributes. Based on the model of auditory-brain model, this study has investigated the relationship between the subjective attributes in the sound field and the factors extracted from the interaural cross-correlation function and autocorrelation function.

In chapter 1, previous studies on the subjective preference and other subjective attributes in the sound field are summarized. The aim of this study has been described after the model of auditory-brain system and the factors extracted from the interaural cross-correlation function and autocorrelation function were described.

In chapter 2, the subjective preference or image shift in relation to the four orthogonal physical factors (the listening level, the initial time delay gap, the reverberation time and the IACC) and the interaural time delay τ_{IACC} was examined in existing sound fields. The interaural time delay τ_{IACC} is related to the sound localization in horizontal plane or balance of sound field. Subjective preference tests by the paired-comparison method were conducted, switching only the loudspeakers on the stage without moving from seat to seat in order to exclude the effects of other physical factors such as visual and tactile senses. As a source signal, music motif B was used. The relationship between the scale value of subjective preference and physical factors obtained by simulation using architectural schemes is examined by the factor analysis. The results shows that the rear source (source 4) is more preferred than that of the other sources. If the IACC is obtained at a certain interaural time delay, then scores decrease rapidly due to the image shift of the sound source. The results of the analysis demonstrate that the theory of calculating subjective preference by use of four physical parameters is supported only when the maximum value of interaural crosscorrelation maintained at $\tau_{IACC} = 0$.

In chapter 3, the apparent source width (ASW) in relation to the IACC and the width of the interaural cross-correlation function W_{IACC} was examined in simulated sound fields. The apparent source width (ASW) which related to the broadening the sound image is correlated to the IACC. The ASW is also related to the spectral component of the source signal. For example, even if the IACC is constant, the ASW increases as the center frequency of octave band noise become lower or as the lower frequency components increase. These facts are reflected in the interaural crosscorrelation function. The peak of the function become broader as the center frequency of octave band noise become lower. Based on the crosscorrelation mechanism in auditory-brain model, it is proposed that these results may be described by factors included in the interaural crosscorrelation function itself, namely, IACC and W_{IACC}. It was examined whether the ASW can be calculated as a function of both the IACC and the W_{IACC}. In this study, the ten percentile width $W_{IACC}^{(0.1)}$ is applied for the practical convenience.

First, the scale values of ASW were obtained by paired comparison tests. The values of IACC were adjusted by controlling the ration of the sound pressure of the two lateral reflections to that of the direct sound. The values of $W_{IACC}^{(0.1)}$ were varied by changing the center frequencies of one-third-octave bandpass noises. The center frequencies were 250 Hz, 500 Hz, 1 kHz, and 2 kHz. Subjects judged which of two sound sources they perceived to be wider. The result shows that the IACC and the $W_{IACC}^{(0.1)}$ contribute to the scale value of ASW independently. The scale value of ASW can be calculated by superposition of two terms the 3/2 power of IACC and the 1/2 power of $W_{IACC}^{(0.1)}$.

In the results of the test for one-third-octave bandpass noises, the value of $W_{IACC}^{(0.1)}$ is constant using one center frequency, even if the value of IACC is different. In this particular case, $W_{IACC}^{(0.1)}$ can be replaced by the center frequency of the noise signal. However, $W_{IACC}^{(0.1)}$ depends on the bandwidth of the noise signal. Second experiments were conducted controlling the $W_{IACC}^{(0.1)}$ by changing the bandwidth of the bandpass noises of 500 Hz center frequency. The bandwidths were 1/3, 1/1, 2 and 3 octave. The result shows that the IACC and the $W_{IACC}^{(0.1)}$ also contribute to the scale value of ASW independently, and the scale value of ASW can be calculated by superposition of two terms the 3/2 power of IACC and the 1/2 power of $W_{IACC}^{(0.1)}$.

To examine whether the formula described in above experiments may be applied to a music signal, third experiment was conducted controlling the delay time of the reflection Δt_1 using a single music source. When the Δt_1 is close to the 0 ms, the value of IACC is increase, and the $W_{IACC}^{(0.1)}$ is changed. The results show that the scale values of ASW for a music signal are also calculated by the same equation for the noise signals.

In chapter 4, subjective preference of cellists for the delay time of a single reflection was examined. The scale values of preference for the delay time of a single reflection were obtained using a paired comparison method, and the results were compared with those for the alto-recorder players and listeners. The results shows that the scale values of preference for both individuals and for global cellists with regard to the delay time of reflection can be expressed by a single approximate formula, normalizing the delay time by the most-preferred delay time observed for different music motif. The most-preferred delay time of a single reflection for each cello soloist can be calculated from the amplitude of the reflection and the minimum value of the effective duration of the running autocorrelation function of the music motifs played by that cellist.

In chapter 5, conclusions and further problems are summarized. The results of this study lead to the conclusions as follows:

(1) Subjective preference in existing sound field can be calculated using the four physical factors and the interaural time delay τ_{IACC}. If the τ_{IACC} is not zero, then the scale value of preference decrease rapidly due to the image shift or unbalanced sound field.

(2) Scale value of ASW can be formulated by superposition of two terms the 3/2 power of IACC and the 1/2 power of $W_{IACC}^{(0.1)}$.

(3) The most-preferred delay time of a single reflection for each cello soloist can be calculated from the amplitude of the reflection and the minimum value of the effective duration of the running autocorrelation function of the music motifs played by that cellist.

It is recommended that the factors extracted from the interaural cross-correlation function, the interaural time delay τ_{IACC} and the width of the interaural cross-correlation function W_{IACC} as well as the IACC are measured in the test of the acoustical condition after construction of the auditorium.

5.2. Application of This Study

This study confirmed the interaural cross-correlation mechanism and autocorrelation mechanism in the proposed model of auditory-brain system. The spatial and temporal physical factors that associated with the right and left cerebral hemispheres are based on theses mechanisms. Both hemispheres may be satisfied by optimizing these factors. In this section, an application of this study for the design of a concert hall is discussed.

The fundamental concept for the acoustic design of a concert hall was derived from the subjective preference theory using the four orthogonal physical factors and is illustrated in Figure 5.1. The specialization of the left and right hemispheres for temporal and spatial factors should be taken into consideration for both listeners and performers. Alternative drawings, for increasing the scale values of preference, should be determined using the data information. The first step is to determine the dominant use of the concert hall under design by selecting a certain range of the τ_e for the source programs, which depends on the type of music and its tempo. The second step is to form the initial drawings of the enclosure so as to optimize the spatial factor IACC. The final goal is to maximize the scale values of preference for both the listeners and the performers, and this is reflected in the final drawing of the concert hall.

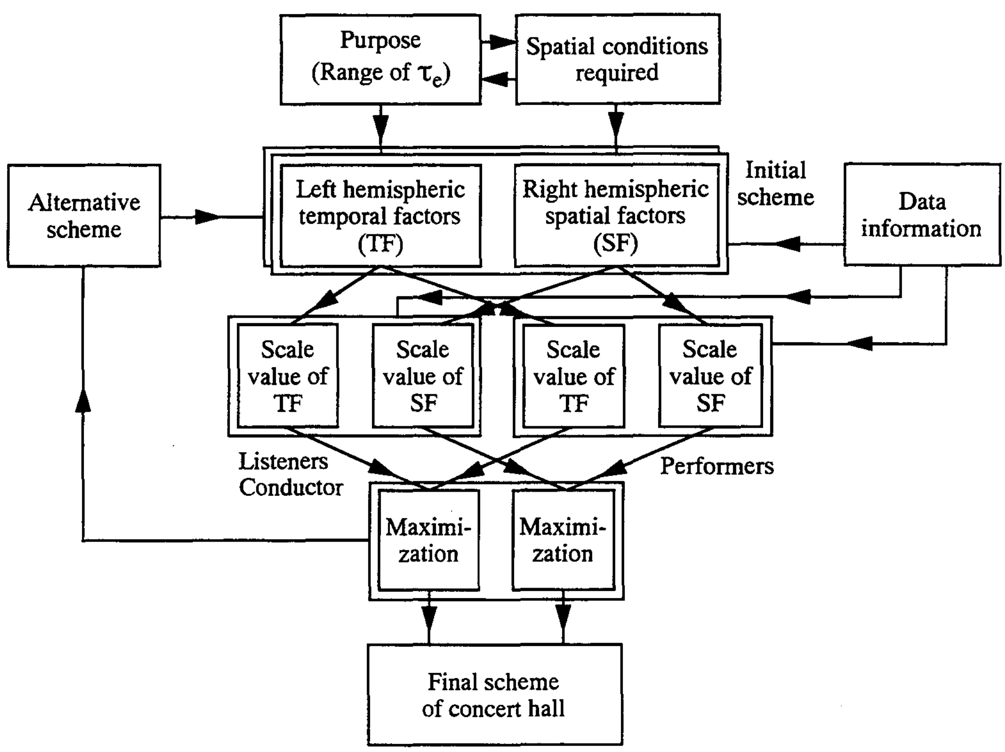


Figure 5.1. Flow chart for the design of a concert hall.

In chapter 2 the subjective preference theory was confirmed in existing sound field. Spatial attribute of the sound field may be depends on the IACC and the W_{IACC} as described in chapter 3. The results in chapter 4 may be applied to the design of the stage enclosure for the performers.

As an application of the theory, a seat selection system was introduced to maximize the preference of each individual with respect to the sound field as described by the four acoustic factors (Ando at al., 1997). Preference tests were performed in a listening room simulating the sound fields with multiple loudspeakers installed in the Kirishima international concert hall. Paired-comparison method is used to obtain the most preferred combination of LL, Δt_1, T_{sub}, and IACC. Several music motifs are used as a sound signal. Since it is assumed here that there is no effect of the order of presentation, the test sound fields were tested using a total of thirty-three pairs, with five levels of LL, Δt_1, T_{sub}, and three levels of IACC. The duration of each stimulus is about 10 s. It takes about 15 minutes for each listener.

Scale values of individual preference as a function of each physical factor were obtained by the simplified method (Ando and Singh, 1996). An area of seats where individual preference is maximized can be found. Examples of preference-test results for three individuals using Suite VI from the "Water Music" by G. F. Handel (τ_e = 62 ms) are shown in Figure 5.2. The seats are classed in three parts according to the scale values of preference. Black seats indicate preferred areas about one-third of all seats in this hall for each subject. Listener A shows a preference similar to the global preference for each factor. Listener B is recommended to sit close to the stage because he prefers a high listening level. The listening level is designed to be nearly constant throughout the hall; however, a large variation in the listening level may be useful for meeting the large range of individual preferences in listening level. Listener C is recommended to sit near the side walls because he prefers a short initial time delay gap. The range of preferred listening level, for example, is much greater than 20 dBA due to the individual difference of the hearing level. With regard to the reverberation time, the range of preferred value is 0.5-4.5 s (Ando and Setoguchi, 1996). The initial time delay gap also has a great range of preferred value. The large individual differences in the most preferred listening level are at least partly related to the individual hearing level. The preferred initial time delay and the preferred reverberation time are associated with an individual preference for "liveness". Generally, the preferred values of LL, Δt_1, and T_{sub} for each individual are quite different, but all of the subjects tested always preferred a small value of IACC. To maximize the individual preference, such facts must be considered. Individual difference of the subjective attributes stated in this study may be discussed in terms of the weighting coefficients for calculating the scale values of ASW or the scale value of preference for performers.

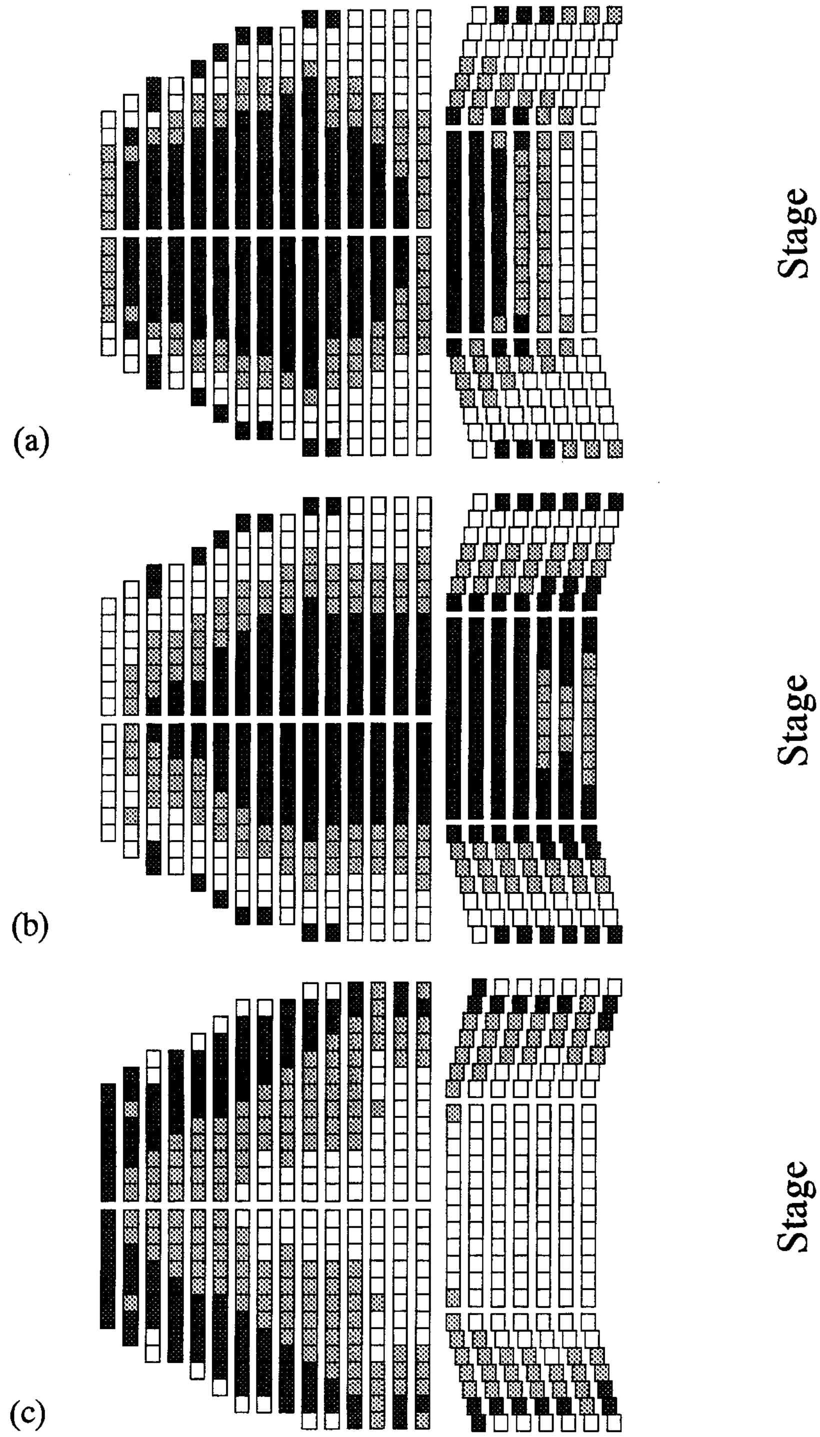


Figure 5.2. Preferred seat area graded into three levels obtained from the results of preference tests: (a) Listener A; (b) Listener B; and (c) Listener C.

5.3. Further Problems

Based on the model of auditory-brain model, the relationship between the subjective attributes on the spatial factor in the sound field and the factors extracted from the interaural cross-correlation function was investigated.

In this study, the factors extracted from interaural cross-correlation function are calculated from the long-time interaural cross-correlation function without any temporal partitioning of the integration interval like 0-80 ms, however, spectrum components of the source signal changes temporally. Therefore, it should be confirmed that the spatial attributes are changed temporally introducing the running interaural cross-correlation function (Yanagawa et al., 1988; Yanagawa, 1997).

The apparent source width (ASW) can be calculated from the two-dimensional factors: IACC and W_{IACC}. The IACC is the factor depends on the sound field, and the W_{IACC} mainly depends on the source signal. However, the subjective diffuseness may to some extent be related to Δt_1 and T_{sub} under the fixed conditions of the IACC and W_{IACC}. The W_{IACC} is affected by the sound field like concert hall or outdoor sound field (Sakai et al., 1998). The relationship between the ASW and the physical factors should be investigated to calculate the ASW at each seat in a concert hall.

Appendix A

Method of Factor Analysis

The method which is applied in the multiple-dimensional-factor analysis of Section 2.4 is briefly described here (Hayashi, 1952; Hayashi, 1954a,b). We give the numeric values to each sub-category of each item and synthesize the responses as we are concerned with behavior patterns.

In this analysis, all items do not need to be scalable. Use the data of n cases. Let A be an outside variable and define s and k as s = 1, 2, ..., R (R is the number of items), and k = 1, 2, ..., K_s (K_s is the number of subcategories in s th item), respectively. Since each case checks only one subcategory in each item, the behavior pattern of the i-case is to be synthesized in the form of

$$\alpha_i = \sum_{s=1}^{K_s} X_s(i) = \sum_{s=1}^{R}\{\sum_{k=1}^{K_s} \delta_i(sk) X_{sk}\}, \tag{A1}$$

where

$$\sum_{k=1}^{K_s} \delta_i(sk) = 1 \tag{A2}$$

and

$\delta_i(sk) = 1$, if the i-case comes under the k th subcategory in the s th item,

$\delta_i(sk) = 0$ otherwise.

α_i, which is called the total score of the i-case, has a numerical value, since X_{sk} has a numerical value.

The correlation coefficient ρ between A and α_i is written as follows:

$$\rho(A,\alpha_i) = \frac{\frac{1}{n}\sum_{i=1}^{n}(A_i - \overline{A})(\alpha_i - \overline{\alpha})}{\sigma_A \sigma_\alpha} \tag{A3}$$

where

$$\overline{A} = \frac{1}{n}\sum_{i=1}^{n} A_i, \quad \sigma_A^2 = \frac{1}{n}\sum_{i=1}^{n}(A_i - \overline{A})^2,$$

$$\overline{\alpha} = \frac{1}{n}\sum_{i=1}^{n} \alpha_i, \quad \sigma_\alpha^2 = \frac{1}{n}\sum_{i=1}^{n}(\alpha_i - \overline{\alpha})^2. \tag{A4}$$

In order to obtain a maximum value, ρ, or to be estimate the outside variable from the behavior pattern, put $\overline{A} = 0$ and $\overline{\alpha} = 0$, because ρ is invariant under a shift of origin. The score of each sub-category can be determined by solving

$$\frac{\partial \rho}{\partial X_{sk}} = 0, \quad (s = 1, 2, ..., R; \; k = 1, 2, ..., K_s). \tag{A5}$$

Appendix B

W_{IACC} defined by the Width of the Interaural Cross-correlation Function Crossing Zero

For the value of the δ in Equation (1.7), the width at the zero crossing, $W_{IACC}^{(1.0)}$ may be employed. This means δ = 1.0 when IACC = 1.0. The scale value of ASW for one-third-octave bandpass noises can again be described by the function of IACC and $W_{IACC}^{(1.0)}$, such that

$$s(ASW) \approx s(IACC) + s(W_{IACC}^{(1.0)}), \tag{B1}$$

$$s(ASW) \approx a'(IACC)^{3/2} + b'(W_{IACC}^{(1.0)})^{1/2}. \tag{B2}$$

The coefficients a' and b' in Equation (B2) is derived from a multiple regression analysis with the term of the 3/2 power for IACC and 1/2 power for $W_{IACC}^{(1.0)}$. Coefficients a' and b' for global results are -1.69 and 1.35, respectively. The maximum error between the measured and calculated scale value of ASW is ±0.18. Similar to the results with δ at 10 percent, the correlation coefficient between the measured scale values of ASW and the calculated scale values of ASW is 0.98 ($p <$ 0.01). Coefficients a' and b' for each individual are listed in Table B1. Standard deviations of the coefficients for individuals are ±0.57 and ±0.33, respectively.

There is little difference between the results for definitions of the $W_{IACC}^{(1.0)}$ and the $W_{IACC}^{(0.1)}$ in calculating the ASW (one-third-octave bandpass noises). Considering the just noticeable difference for IACC, however, the definition of the ten percentile width seems to be more suitable for speech and music, or signals of broader spectral content.

Table B1. Coefficients a' and b' in Equation (B2) for each individual using one-third octave bandpass noises, together with the correlation coefficients between the measured scale values of ASW and the calculated scale values of ASW by Equation (B2); the 95 percent reliability; and the maximum error.

Subject	a'	b'	Correlation coefficient	95 percent reliability	Maximum error
Global	-1.69	1.35	0.98	±0.09	±0.18
SH	-1.26	1.40	0.88	±0.18	±0.47
TS	-1.56	1.75	0.97	±0.11	±0.26
CC	-1.11	1.55	0.97	±0.10	±0.21
SY	-1.00	1.60	0.91	±0.17	±0.55
MK	-2.26	1.08	0.95	±0.17	±0.40
ST	-2.61	1.08	0.95	±0.16	±0.52
TH	-2.07	0.74	0.88	±0.19	±0.58
FK	-1.05	1.79	0.89	±0.20	±0.53
NK	-1.84	1.20	0.81	±0.23	±0.77
OS	-2.14	1.18	0.94	±0.14	±0.39
Mean SD	-1.69±0.58	-1.35±0.88			

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