



DISSIMILARITY JUDGMENTS IN RELATION TO TEMPORAL AND SPATIAL FACTORS FOR THE SOUND FIELD IN AN EXISTING HALL

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In relation to the temporal and spatial factors of sound fields, dissimilarity judgments for different source locations on a stage were performed. This study is based on the model of the auditory–brain system, which consists of the autocorrelation and crosscorrelation mechanisms for sound signals arriving at two ears and the specialization of human cerebral hemispheres. There are three temporal factors (τ_1 , ϕ_1 and τ_e) extracted from the autocorrelation function and four spatial factors (LL , $IACC$, τ_{IACC} and W_{IACC}) from the interaural crosscorrelation function of binaural signals. In addition to these temporal and spatial factors, the orthogonal factors of the subjective preference for sound field (Δt_1 and T_{sub}) were taken into account. The psychological distance between sound fields of different source locations on the stage were calculated by using these temporal, spatial and orthogonal factors of sound fields. Using these distances and their linear combination, dissimilarity can be calculated. Results of multivariable analysis show that the calculated scale values of dissimilarity agree well with the measured scale values.

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1. INTRODUCTION

In order to design an excellent sound field in a concert hall, it is necessary to identify the significant physical factors by subjective evaluation. If enough were known about the auditory cognitive system in the brain, a design method for concert halls could be established according to guidelines derived from the knowledge of this system. A model of the auditory–brain system (Figure 1) was proposed by Ando [1], correlating subjective attributes with auditory evoked potentials, including continuous brain wave (CBW), as responding to variations of acoustical factors. This model consists of autocorrelators and an interaural crosscorrelator acting on the pressure signals arriving at the two ears. Furthermore, the model takes into account the specialization of the left and right human hemispheres.

A theory of primary sensations and spatial sensations responding to environmental noise has been proposed [2] based on the model of an auditory–brain system. Primary sensations—loudness, pitch, timbre and temporal duration- and spatial sensations—subjective diffuseness, image shift of sound source and apparent source width (ASW)—can be described by the temporal and spatial factors extracted from the autocorrelation function (ACF) and the interaural crosscorrelation function (IACF) respectively. It has been shown that environmental noise can be characterized by these factors [3–5]. Fundamental subjective attributes for the sound field in a concert hall are accurately described by the

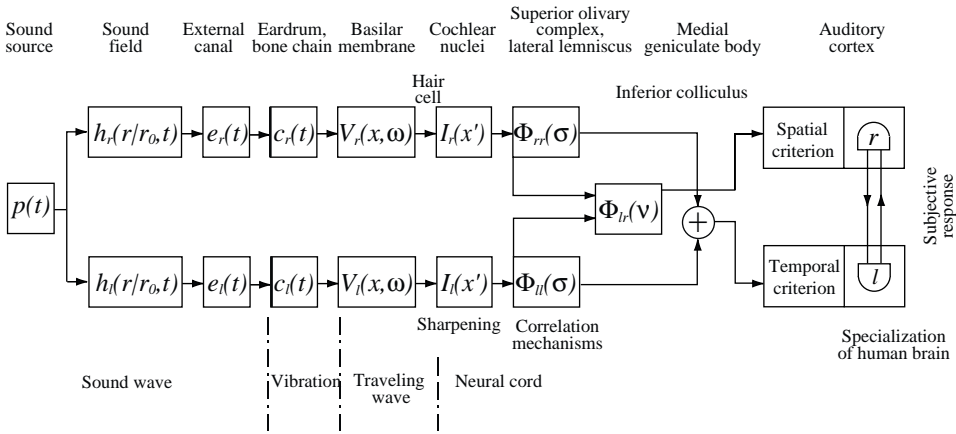


Figure 1. Model of the auditory–brain system with autocorrelation and interaural crosscorrelation mechanisms and specialization of human cerebral hemispheres.

model of auditory–brain system when taking into account the contributions of the ACF and IACF mechanisms. For example, the speech intelligibility of a spoken syllable with a single reflection can be calculated from temporal factors extracted by the ACF [6, 7]. In concert hall acoustics, the theory of subjective preference allows one to calculate the scale values of subjective preference in terms of four orthogonal factors: the listening level (LL), the initial time-delay gap between the direct and the first reflection (Δt_1), the subsequent reverberation time (T_{sub}), and the interaural correlation coefficient ($IACC$) [1].

Yamaguchi [8] carried out a dissimilarity experiment studying the differences between different seats in an existing concert hall and identified two significant factors: the sound pressure level and the reverberation characteristics. Edwards [9] also tested dissimilarity by studying the differences between different halls and reported that the early echo pattern, the reverberation time RT , and the volume level were the significant factors. Sato *et al.* [10] and Cocchi *et al.* [11] confirmed the effectiveness of the theory of subjective preference through investigations in existing concert halls. Sato *et al.* [12] reconfirmed the effectiveness of the theory in an existing opera house.

In this study, dissimilarity judgments are obtained for a sound field with different source locations on the stage of an existing hall. The obtained results were used to examine, through multivariate analysis, the relationships between the dissimilarity judgments and the physical factors based on the auditory–brain system of sound fields and the theory of subjective preference.

2. PHYSICAL FACTORS BASED ON THE AUDITORY–BRAIN SYSTEM

2.1. TEMPORAL FACTORS EXTRACTED FROM THE ACF

The power density spectra in the neural activities in the left and right auditory pathways show a sharpening effect [13, 14]. This information is sufficient to attain an approximation of the ACF of the signals at both ears.

The ACF is defined by

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

where $p'(t) = p(t)*s(t)$, with $s(t)$ being ear sensitivity. For practical convenience, $s(t)$ can be chosen as the impulse response of an A-weighting network. Mouri *et al.* reported that the integration interval $2T$ may be set as $2T \approx 30(\tau_e)_{min}$ [15]. In this study, the integration interval was set up with 2 s satisfying the condition. The ACF and power density spectrum mathematically contain the same information.

Temporal factors extracted from the ACF are defined as follows. The first factor is the effective duration of running ACF, τ_e . This factor is defined by the 10-percentile delay representing repetitive features, or a kind of reverberation, within the source signal itself. The τ_e is obtained from the decay rate for the range from 0 to -5 dB of the normalized ACF. The second and third factors are the amplitude and the delay time of the first dominant peak of the normalized running ACF represented, respectively, as ϕ_1 and τ_1 . It was found that τ_1 is the dominant factor of perceived pitch and ϕ_1 relates to the intensity of perceived pitch.

2.2. SPATIAL FACTORS EXTRACTED FROM THE IACF

The auditory-brain model considers the interaural crosscorrelation mechanism between the two auditory pathways [16]. To specify the spatial characteristics of the sound field, binaural measurements must be made. The fundamental spatial attributes of a sound field are related to the IACF. The IACF between the sound signals at both ears, $f_l(t)$ and $f_r(t)$, is defined by

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

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

The normalized IACF is defined by

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{[\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}}, \quad (3)$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the ACFs at the origin of the time delay for the left and right ears respectively. These values correspond to the equivalent sound pressure level.

The spatial factors are extracted as fine structure of the running IACF. The first factor is the geometrical mean of sound energies arriving at both ears, listening level, LL . This factor is expressed by

$$LL = \frac{10 \log[\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}}{\Phi^{(ref)}(0)}, \quad (4)$$

where

$$\Phi^{(ref)}(0) = [\Phi_{ll}^{(ref)}(0)\Phi_{rr}^{(ref)}(0)]^{1/2}. \quad (5)$$

Here, $\Phi^{(ref)}(0)$ is the geometrical mean of the ACF of binaurally recorded signals at $\tau = 0$, with the reference position indicated by equation (5). The selected reference position is 1 m from the sound source.

The second factor is the $IACC$, which is the maximum value of the normalized IACF for the time delay, within ± 1 ms, which correlates with subjective diffuseness [17, 18]. The third and fourth factors are interaural time delay, τ_{IACC} , and width of the running IACF, W_{IACC} . The factor τ_{IACC} is interaural time delay at the maximum peak, which determines $IACC$. This factor corresponds to the horizontal sound localization and the balance of the

sound field. The factor W_{IACC} is defined as the time interval of the IACF spanning two points within 10% of the maximum IACF value. This factor is strongly related to the apparent source width [6].

2.3. ORTHOGONAL FACTORS OF THE SOUND FIELD FOR SUBJECTIVE PREFERENCE

As described in section 1, the theory of subjective preference allows one to calculate the scale value of subjective preference for a sound field in terms of the following four orthogonal acoustical factors: the listening level, LL , the initial time-delay gap between the direct and the first reflection, Δt_1 , the subsequent reverberation time, T_{sub} , and the magnitude of the IACF, $IACC$. These factors have been identified in systematic investigations of sound fields through both computer simulation and listening tests (paired-comparison tests) [1]. The subjective preference theory has also been validated by tests in actual concert halls and opera houses [10–12].

3. METHOD

3.1. SOURCE SIGNAL

A reverberation-free signal of orchestral music (“Water Music” Suite No. 2-Alla Hornpipe by Handel) was used as a source signal. The duration of the source signal was 4 s. In subjective preference theory, a music source is characterized in terms of the running autocorrelation function (ACF) of the source signal after passing through an A-weighted network. The ACF analysis, with an integration interval $2T = 2.0$ s and running step of 100 ms, was carried out and factors $\Phi(0)$, τ_e , τ_1 , and ϕ_1 were extracted as shown in Figure 2. The value of $[\Phi(0)]_{max}$ is indicated by an arrow at $\tau = 0.5$ s. For the τ_e factor, the minimum value of the effective duration of the source signal, which is strongly related to the preferred conditions of temporal factors, was 46 ms.

3.2. DISSIMILARITY JUDGMENTS

Dissimilarity judgments were performed in a multi-purpose hall, the 400-seat ORBIS Hall in Kobe as shown in Figure 3. Six loudspeakers were placed on the stage. Twenty listeners were divided into four groups and seated at specific positions. Without moving to different seats, dissimilarity judgments were performed while switching six source locations to obtain a scale value of dissimilarity. The listeners were asked to judge the subjective difference as an overall impression between the paired stimuli on a linear scale that has two extreme ends: “no difference” and “extremely different.” The judgment conditions consisted of 15 pairs representing possible combinations of the six sound fields at each listener’s location. The silent interval between paired stimuli was 1 s. Each pair of sound fields was separated by an interval of 5 s, and the pairs were arranged in random order. Each session was repeated five times. In order to construct a scale value of dissimilarity among sound stimuli for the dependent variable, the original data obtained by dissimilarity judgment were categorized into seven categories. A method of successive categories [19] was applied to the categorized data. The scale value of dissimilarity for each pair of source locations at seat positions A, B, C and D is listed in Table 1.

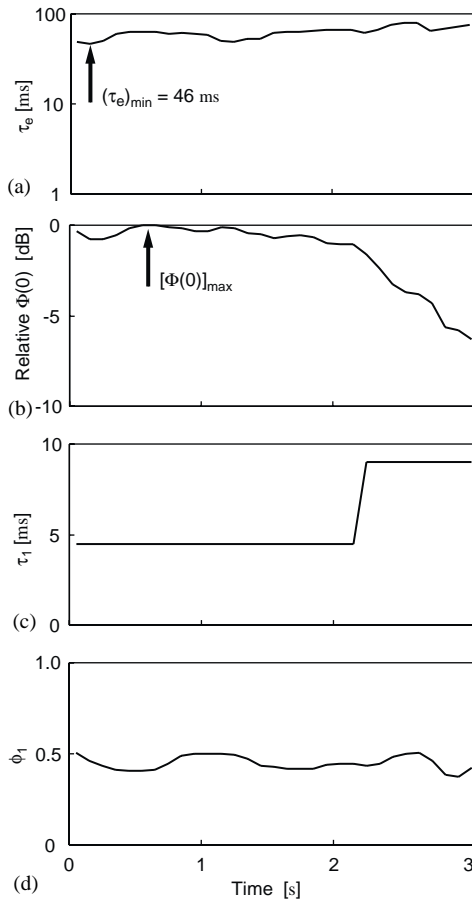


Figure 2. Measured factors of running ACF of the source signal used in the experiment. The integration interval of running ACF, $2T$, was 2.0 s, with a 100 ms interval as a function of time. (a) τ_e ; (b) relative $\Phi(0)$, obtained as relative to the maximum value at $\tau = 0.5$ s; (c) τ_1 ; and (d) ϕ_1 .

3.3. MEASUREMENTS OF ACOUSTICAL FACTORS

To measure the acoustical factors extracted from ACF and IACF, the music signal used in the dissimilarity judgments was reproduced from each loudspeaker used for dissimilarity judgments. The signal was recorded at each listening position, through two microphones at both ear entrances of a person facing the center of the stage. To obtain the impulse responses, an MLS signal was reproduced from each loudspeaker [16].

The running ACF and IACF of the recorded signals after passing the A-weighting network were calculated by an integration interval $2T = 2.0$ s, and running step of 100 ms. Values of τ_1 and ϕ_1 were calculated from running ACF analysis. The value of τ_1 was obtained by the maximum peak of ACF in the time range between $50 \mu\text{s}$ and 30 ms corresponding to the human audible range. The value of ϕ_1 defined by the amplitude at τ_1 was also determined. From the running IACF analysis, running values of LL , $IACC$, τ_{IACC} , and W_{IACC} were calculated.

After obtaining the binaural impulse responses, values of Δt_1 and T_{sub} were calculated. The value of Δt_1 was defined by the time difference between the arrival time of the direct sound and that of the reflection, which is the maximum energy in the impulse responses.

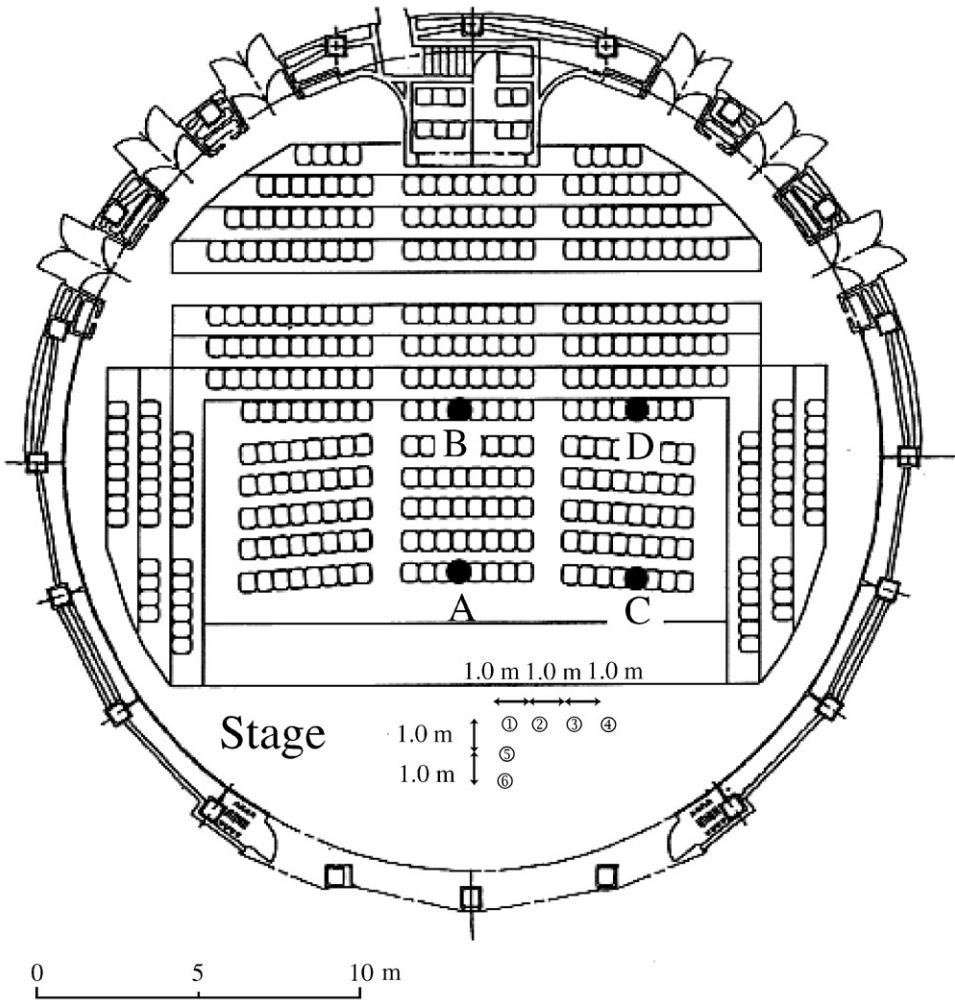


Figure 3. Plan of the "ORBIS Hall" in which dissimilarity judgment was made. A–D: listeners' locations. ①–⑥: source locations changed in the paired comparison tests.

From the two Δt_1 values, the one with the largest amplitude obtained from binaural impulse responses was selected as the Δt_1 of each loudspeaker position and each listening position [20, 21]. For T_{sub} , 500 Hz and 1 kHz octave band center frequencies were adopted, since these frequency ranges are the dominant frequencies of the source signal.

The measured temporal and spatial factors obtained by running ACF, IACF, and binaural impulse response analyses are shown in Figure 4. The factors extracted from the ACF and IACF were chosen from a short time interval centered on the time of $(\tau_e)_{min}$ of the source signal [22], because subjects were assumed to judge this instance as the most sensitive and active portion of the source signal.

3.4. MULTIPLE REGRESSION ANALYSIS

In order to determine a relationship between the scale values and physical factors obtained by the measurement, the data were analyzed by multiple regression analysis. As

TABLE 1

Scale values of dissimilarity for each pair of source locations at seat positions A, B C and D

Pair of source locations	Seat position			
	Position A	Position B	Position C	Position D
1-2	1.4	0.8	0.8	0.9
1-3	1.9	1.7	1.8	1.6
1-4	2.3	2.0	2.5	2.4
1-5	0.7	0.9	0.8	0.7
1-6	1.3	1.0	1.4	1.0
2-3	0.8	0.6	1.2	1.3
2-4	1.2	1.2	2.2	2.0
2-5	1.6	1.2	0.7	0.9
2-6	1.8	1.4	0.8	0.6
3-4	0.5	0.4	1.6	1.2
3-5	2.1	1.9	1.8	1.7
3-6	2.1	2.0	1.4	1.7
4-5	2.4	2.0	2.2	2.1
4-6	2.2	2.1	2.0	2.0
5-6	0.4	0.4	0.9	0.8

explanatory variables, a distance between paired stimuli was introduced by the factors extracted from the running ACF and the running IACF. In addition to these factors, the orthogonal factors of the subjective preference of sound field were also taken into consideration.

The distances between variables of each factor were calculated for each sound field. The distance D_x between the sound fields of a and b for each factor, x , was calculated in the following manner. Subjective preference, in relation to temporal factors of sound fields, was postulated to be subjectively determined at the most active music segment, coinciding with a minimum τ_e . Therefore, factors extracted from running ACF and IACF were chosen at the time frame where the source signal showed minimum τ_e [15, 22].

Temporal factors:

$$D_{\tau_1} = |\log(\tau_1)^a - \log(\tau_1)^b|, \quad (6)$$

$$D_{\phi_1} = |\log(\phi_1)^a - \log(\phi_1)^b|. \quad (7)$$

Spatial factors:

$$D_{LL} = |(LL)^a - (LL)^b|, \quad (8)$$

$$D_{IACC} = |(IACC)^a - (IACC)^b|, \quad (9)$$

$$D_{\tau_{IACC}} = |(\tau_{IACC})^a - (\tau_{IACC})^b|, \quad (10)$$

$$D_{W_{IACC}} = |(W_{IACC})^a - (W_{IACC})^b|. \quad (11)$$

Orthogonal factors for sound fields:

$$D_{\Delta t_1} = \left| \log \left(\frac{\Delta t_1}{[\Delta t_1]_p} \right)^a - \log \left(\frac{\Delta t_1}{[\Delta t_1]_p} \right)^b \right|, \quad (12)$$

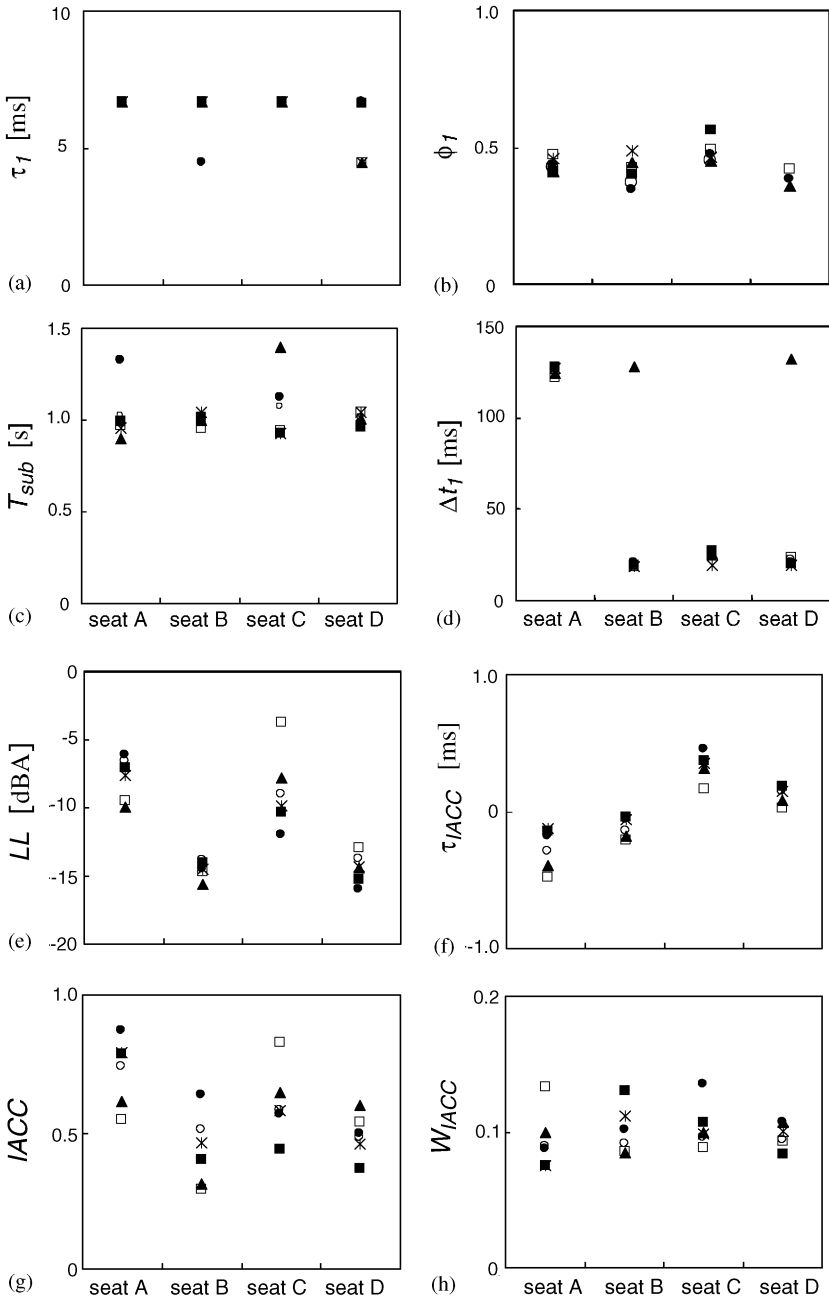


Figure 4. Measured physical factors at each listener’s location obtained from acoustical measurements. (a) τ_1 ; (b) ϕ_1 ; (c) T_{sub} ; (d) Δt_1 ; (e) LL ; (f) τ_{IACC} ; (g) $IACC$; and (h) W_{IACC} . ●, values measured for source location ①; ○, values measured for source location ②; ▲, values measured for source location ③; □; values measured for source location ④; ■: values measured for source location ⑤; and *, values measured for source location ⑥.

$$D_{T_{sub}} = \left| \log \left(\frac{T_{sub}}{[T_{sub}]_p} \right)^a - \log \left(\frac{T_{sub}}{[T_{sub}]_p} \right)^b \right|, \tag{13}$$

where $D_{\Delta t_1}$ and $D_{T_{sub}}$ are the distances of the normalized values for the most preferred Δt_1 , $[\Delta t_1]_p$ and T_{sub} , $[T_{sub}]_p$ respectively. The preferred values are expressed approximately as $[\Delta t_1]_p \approx (1 - \log_{10} A)(\tau_e)_{min}$, A being the total pressure amplitude of all reflections, and $[T_{sub}]_p \approx 23(\tau_e)_{min}$. The distances of temporal factors D_{τ_1} , D_{ϕ_1} , $D_{\Delta t_1}$ and $D_{T_{sub}}$ were calculated using logarithmic values, since temporal factors are assumed to be perceived according to the Weber–Fechner law. The explanatory variables in the analysis were: D_{LL} , D_{τ_1} , D_{ϕ_1} , D_{IACC} , $D_{\tau_{IACC}}$, $D_{W_{IACC}}$, $D_{\Delta t_1}$ and $D_{T_{sub}}$. In the multiple regression analysis, the distances for factors were combined linearly, using an expression given by

$$D = aD_{LL} + bD_{\tau_1} + cD_{\phi_1} + dD_{IACC} + eD_{\tau_{IACC}} + fD_{W_{IACC}} + gD_{\Delta t_1} + hD_{T_{sub}}, \quad (14)$$

where D is a dependant variable to be calculated and a, b, c, d, e, f, g and h are the coefficients to be evaluated. The coefficients were obtained by a step-wise regression method. In this multiple regression model, no regression constant was included.

4. RESULTS

Prior to the multiple regression analysis, correlation coefficients among explanatory variables were obtained as listed in Table 2. Results show that $D_{W_{IACC}}$, D_{LL} and D_{IACC} highly correlated with $D_{\tau_{IACC}}$ (correlation coefficients with $D_{\tau_{IACC}}$ were 0.59, 0.56, and 0.54 respectively). The value of $D_{W_{IACC}}$ is a significant factor for determining ASW if source signals of different frequency ranges are used [6], but had a minor effect in this experiment. To avoid the effect of multicollinearity, which causes problems in estimating the effects of explanatory variables on a dependant variable, $D_{W_{IACC}}$ was excluded from the explanatory variables due to correlation with the significant factor $D_{\tau_{IACC}}$.

By applying multiple regression analysis to the dependent variables and the explanatory variables, normalized partial regression coefficients were obtained as listed in Table 3.

TABLE 2

Correlation coefficients between physical factors obtained from the acoustical measurements

	D_{LL}	D_{τ_1}	D_{ϕ_1}	D_{IACC}	$D_{\tau_{IACC}}$	$D_{W_{IACC}}$	$D_{\Delta t_1}$	$D_{T_{sub}}$
D_{LL}	1.00	-0.26*	-0.30*	0.41**	0.56**	0.21	-0.10	0.28*
D_{τ_1}		1.00	0.42**	0.08	-0.18	-0.23	0.13	-0.34**
D_{ϕ_1}			1.00	0.38**	-0.28*	-0.04	0.23	-0.29*
D_{IACC}				1.00	0.54**	0.26	0.15	0.03
$D_{\tau_{IACC}}$					1.00	0.59**	-0.05	0.04
$D_{W_{IACC}}$						1.00	-0.02	-0.11
$D_{\Delta t_1}$							1.00	-0.25
$D_{T_{sub}}$								1.00

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

TABLE 3

Partial regression coefficients for significant factors obtained by multiple regression analysis with normalized partial regression coefficients

	D_{τ_1}	D_{ϕ_1}	$D_{\tau_{IACC}}$	$D_{\Delta t_1}$	$D_{T_{sub}}$
Partial regression coefficients	1.91	3.37	7.59	0.37	3.90
Normalized partial coefficients	0.10	0.15	0.69	0.08	0.17
p value	0.02	<0.01	<0.01	<0.01	0.05

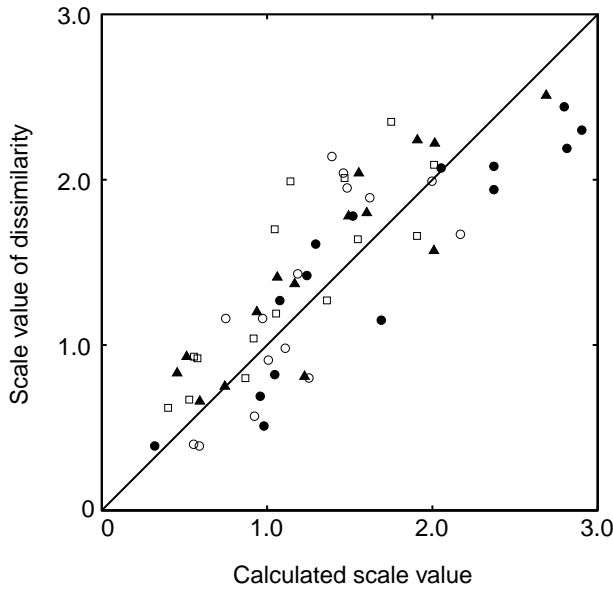


Figure 5. Relationships between calculated scale values when applying equation (15) obtained by the regression analysis for all seat positions and scale values of dissimilarity at each seat position ($r = 0.84$; $p < 0.01$). ●, values obtained at seat position A ($r = 0.92$; $p < 0.01$); ○, values obtained at seat position B ($r = 0.79$; $p < 0.01$); ▲, values obtained at seat position C ($r = 0.90$; $p < 0.01$); □, values obtained at seat position D ($r = 0.84$; $p < 0.01$).

D_{LL} and D_{IACC} were eliminated from the explanatory variables because $p \geq 0.1$; namely, these factors were not significant for dissimilarity in this experiment.

Normalized partial regression coefficients obtained here were 0.10 (D_{τ_1} ; $p = 0.02$), 0.15 (D_{ϕ_1} ; $p < 0.01$), 0.69 ($D_{\tau_{IACC}}$; $p < 0.01$), 0.08 ($D_{\Delta t_1}$; $p < 0.01$), and 0.17 ($D_{T_{sub}}$; $p = 0.05$). The normalized partial regression coefficients indicated that the effect of $D_{\tau_{IACC}}$ on dissimilarity was the maximum (0.69). D_{ϕ_1} and $D_{\Delta t_1}$ also significantly contributed to the dissimilarity ($p < 0.01$).

In order to examine the relationships between the scale value obtained by dissimilarity judgments and the dissimilarity calculated by the physical factors, the dissimilarity D was obtained in the following manner:

$$D \approx 1.91D_{\tau_1} + 3.37D_{\phi_1} + 7.59D_{\tau_{IACC}} + 0.37D_{\Delta t_1} + 3.90D_{T_{sub}}. \quad (15)$$

Figure 5 shows the relationship between scale values of dissimilarity at each seat position and the calculated values by applying the partial regression coefficients obtained from the regression analysis for all seat positions. The correlation coefficients between scale values of dissimilarity and calculated values at each seat position were 0.92 ($p < 0.01$) at seat position A, 0.79 ($p < 0.01$) at seat position B, 0.90 ($p < 0.01$) at seat position C, and 0.84 ($p < 0.01$) at seat position D. The total correlation coefficient between scale values of dissimilarity and calculated values of dissimilarity for all seats was 0.84 ($p < 0.01$).

5. DISCUSSION

In this experiment, under the condition of changing source location, the effect of a change in τ_{IACC} was dominant for dissimilarity. However the effects of changes

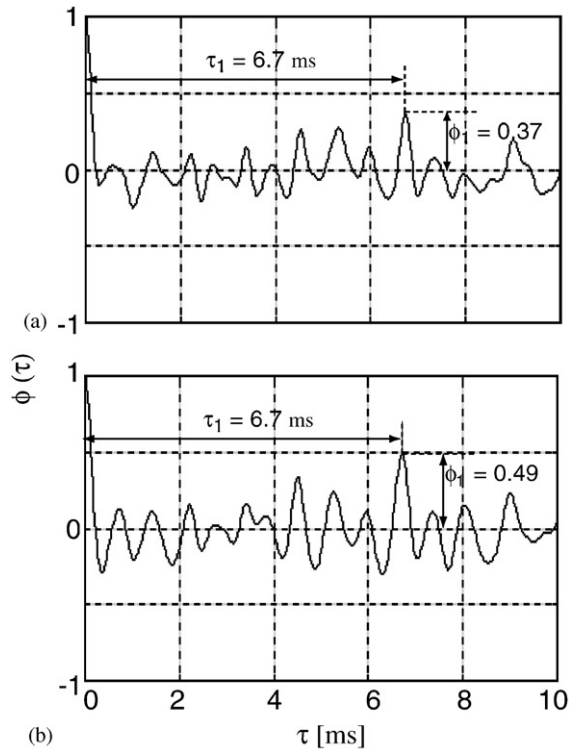


Figure 6. Examples for ACF waveform. (a) source location ② at seat position B; source location ⑥ at seat position B.

in D_{LL} and D_{IACC} could not be taken into account because of the high correlation with $D_{\tau_{IACC}}$. The most important result was that D_{ϕ_1} and $D_{\Delta t_1}$, which are temporal factors, significantly contributed to dissimilarity. This implies that subjects judged dissimilarity by not only a change in spatial factors but also a change in temporal factors. The subjective preference theory [1] predicts that both temporal and spatial factors of sound fields affect subjective preference when forming an overall impression of a sound field. The same effects may be obtained for dissimilarity, based on the overall responses.

Figure 6 illustrated the examples of the running ACF of source locations 2 and 6 at seat position B. A difference can be seen in the ACFs affected by the different transmission characteristics of sound fields. As for the effect of ϕ_1 on dissimilarity, it can be said that the subjects perceive the difference in sound fields through the difference in ACF. This result corresponds to those obtained by Yost [23], who demonstrated that pitch perception of iterated rippled noise is dominantly affected by the first ACF peak of the stimulus signal.

6. CONCLUDING REMARKS

Results of multiple regression analysis show that psychological distance can be accurately described by the temporal and spatial factors obtained by ACF and IACF as

well as the orthogonal factors extracted from binaural impulse response analyses based on the auditory–brain system and the subjective preference theory.

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