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Experimental study on stage acoustics for ensemble performance in chamber music

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Abstract: In order to investigate the effect of room acoustic conditions on music players, subjective experiments on professional musicians using digital sound field simulation technique were conducted. In the simulation system, two anechoic rooms were acoustically connected and the situation where two musicians play in ensemble on a hall stage has been virtually realized. Using this system, subjective experiment for ease of chamber music performance on professional musicians was performed and the preferable condition for ensemble performance was investigated. From the experimental results, the relationships between physical characteristics and psychological judgments by the musicians were considered.

Keywords: Stage acoustics, Concert hall design, Sound field simulation, Ensemble performance

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1. INTRODUCTION

In concert hall design, the acoustic conditions for music players on the stage should be considered as well as those for the audience. In this respect, stage acoustics, we have made several investigations by subjective experiment up to now. In these studies, we have developed a sound field simulation technique using six-channel real time convolution system to examine the musicians' sensation in an artificial concert hall and investigated the relationship between acoustic parameters and subjective impression in solo performance [1].

In the study of stage acoustics, the acoustic conditions for ensemble performance are also important and several researches have been made on this point [2–5]. The authors also have started an experiment for ensemble performance by two players on a stage by expanding the sound field simulation technique mentioned above, in which two anechoic rooms and 24 channel digital convolution system are used. The applicability of this system to psycho-acoustic experiments on ensemble performance was examined in the preliminary experiment on professional musicians [6]. Based on the experiences obtained in the preliminary study, we have performed a series of subjective experiments on the acoustic conditions for chamber music performance under a further detailed condition.

In this paper, (1) the measurement results of the acoustic conditions on the stage of various types of concert halls, (2) the acoustic simulation system used for the experiment, (3) the experimental conditions and (4) the results of the subjective judgment tests by professional music players are presented. From the experimental results, the relationships between the physical characteristics of the sound field and players' subjective impression of ease of chamber music performance are discussed.

2. ACOUSTIC PROPERTIES IN STAGE AREA

In order to investigate the acoustic conditions on stages, impulse response measurement was performed in seven concert halls in Japan (see Table 1).

2.1. Measurement Method

The measurement points were chosen so as to represent the players' positions of chamber music as shown in Fig. 1. To obtain the sound transmission properties for the two

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Table 1 Concert halls under measurement.

Hall	A	B	C	D	E	F	G
Seats	440	761	826	1,502	1,801	2,006	2,020
Volume [m^3]	4,228	6,600	9,418	20,500	18,500	21,000	22,776
Stage area [m^2]	102	100	207	209	240	250	290
Style	shoebox	proscenium	proscenium	proscenium	shoebox	center stage	shoebox
RT(audience area) [s]	1.8	2.0	1.9	1.9	2.1	2.2	2.4

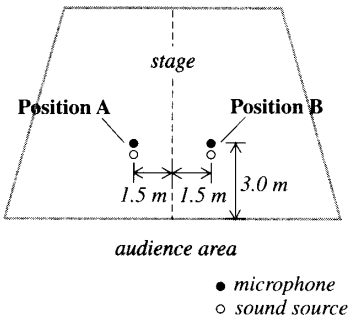


Fig. 1 Measurement positions on stages.

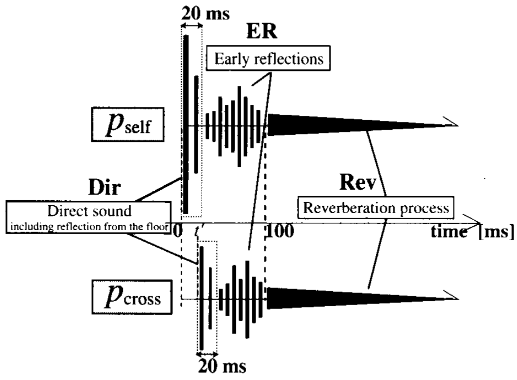


Fig. 3 Separation of impulse responses.

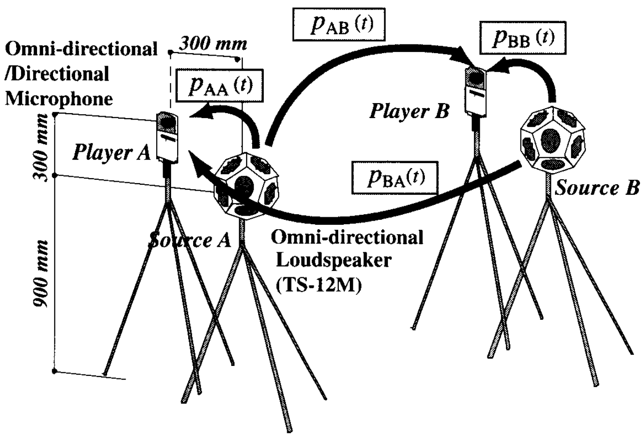


Fig. 2 Configuration of measurement instruments.

players on a stage, A and B, four transmission paths, $p_{AA}(t)$, $p_{BB}(t)$, $p_{AB}(t)$, and $p_{BA}(t)$, were assumed as shown in Fig. 2. Here, $p_{AA}(t)$ and $p_{BB}(t)$ (they are called $p_{self}(t)$ together) are the sound transmission characteristics from the musical instrument of the player A/B to the player A/B, respectively, and $p_{BA}(t)$ and $p_{AB}(t)$ (they are called $p_{cross}(t)$ together) are those from the musical instrument of the player A/B to the player B/A, respectively.

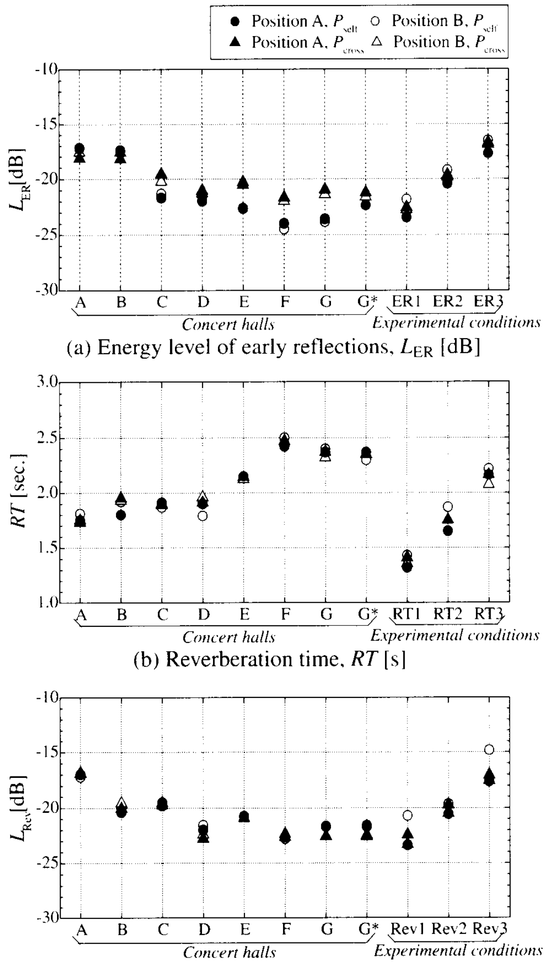
In the measurement, a dodecahedral loudspeaker was used to model the musical instruments and an omni-directional or a uni-directional microphone (Sony C48) with a cardioid directivity was located just behind the sound source as shown in Fig. 2. In the measurement using the uni-directional microphone, the directional impulse responses in six orthogonal directions were measured by rotating the microphone in 90-degree increments and used for the sound field simulation mentioned in section 3.1.

2.2. Results

In order to examine the transient process, the impulse responses measured through an omni-directional microphone were divided into three components as shown in Fig. 3; the direct sound including the reflection from the floor (Dir), the early reflections (ER) and the reverberation process (Rev). These components in an impulse response were separated in time domain and the energy (squared and integrated sound pressure) of respective components were calculated and expressed in level [6]. Here, the energy level of the early reflections and that of the reverberation process were indicated as a relative level to the direct sound of $p_{self}(t)$; L_{ER} and L_{Rev}, respectively.

Figure 4 shows the results of L_{ER}, L_{Rev} and reverberation time (RT) which is obtained by the integrated impulse response method. The results are for the middle frequency range in two octave band including 500 Hz and 1 kHz bands. RT was read from the later part of the impulse responses excluding the effect of the direct sound and early reflections.

In these figures, it can be seen that all quantities of L_{ER}, L_{Rev} and RT are different for respective concert halls. When setting the experimental conditions mentioned below, these data were taken into consideration.



(a) Energy level of early reflections, L_{ER} [dB]

(b) Reverberation time, RT [s]

(c) Energy level of reverberation, L_{Rev} [dB]

G* : the condition with stage risers in Hall G

Fig. 4 Measurement results in real concert halls.

3. EXPERIMENTAL SETUP

In order to simulate the situation where two musicians play in ensemble on a stage, artificial sound fields were constructed as follows.

3.1. Sound Field Simulation System

Acoustic condition of ensemble performance between two players on the stage of a concert hall was simulated by applying the 6-channel sound field simulation technique [1]. That is, the 6-channel directional impulse responses measured in real halls were used to synthesize three dimensional sound using six loudspeakers in an anechoic room. In order to simulate the sound field conditions for two players separately, two anechoic rooms (room-A: 7meters cubed and room-B: 4.0 m × 6.8 m × 7.0 m) were coupled acoustically as shown in Fig. 5 and the four sets of 6-channel directional impulse responses installed in the digital convolution system (24 channel in total) were used to synthesize the sounds from six directions for each player. For the dry music signal, the sound from each player's instrument was detected using a uni-directional microphone (Sony, C48) set at a point close to the player in each room. The signals were convolved with the 6-channel directional impulse responses for each of $p_{self}(t)$ and $p_{cross}(t)$, respectively, using 24-channel real-time digital convolution system. In the case of $p_{self}(t)$, the direct sound from the sound source and the reflection from the stage floor in the directional impulse response signals were excluded. The convolved signals for $p_{self}(t)$ and $p_{cross}(t)$ were mixed for each channel and reproduced through the six loudspeakers (TANNOY, T12) arranged in each room.

For this simulation system, the applicability to psycho-acoustic experiment on ensemble performance was examined by performing a preliminary subjective experiment [6]. Through the investigation, it has been assured that the musicians can get a feeling of acoustic reality of performing on a real stage and distinguish the differences of acoustic conditions.

3.2. Experimental Conditions

To set the experimental conditions assuming chamber music performance, a set of directional impulse responses, 24 in total, measured in Hall A of relatively small seat capacity (see Table 1) were used and the impulse responses were divided into three parts as shown in Fig. 3. Then, three parameters, magnitude of the early reflections (L_{ER}), reverberation time (RT) and magnitude of the reverberation process (L_{Rev}) were changed in three steps, respectively as shown in Table 2. The values of these parameters were decided by referring the measurement results in the real concert halls shown in Fig. 4 and the preliminary experiment [7]. For all conditions, the component of the direct sound included in $p_{cross}(t)$ was kept constant and the conditions of the early reflection and the reverberation process were varied by changing the filter coefficients of the convolvers.

To examine these experimental conditions, $p_{self}(t)$ and $p_{cross}(t)$ at the center point in each simulated sound field were measured using the same set-up as shown in Fig. 2, where an omni-directional microphone was used and the experimental parameters (L_{ER}, RT, L_{Rev}) were measured. In addition, EEL proposed by Gade [4] was also calculated as follows

$$EEL = 10\log\left(\int_{0\,\mathrm{ms}}^{80\,\mathrm{ms}} p_{cross}^2(t)dt \Bigg/ \int_{0}^{10\,\mathrm{ms}} p_{self}^2(t)dt\right)$$

where $t = 0$ is the time when the direct sound of $p_{self}(t)$ arrives. The measurement results of these parameters in the middle frequency range (2 octave band including 500 Hz and 1 kHz octave bands) are shown in Fig. 4 and in Table 2 (a) for room A and in Table 2 (b) for room B.

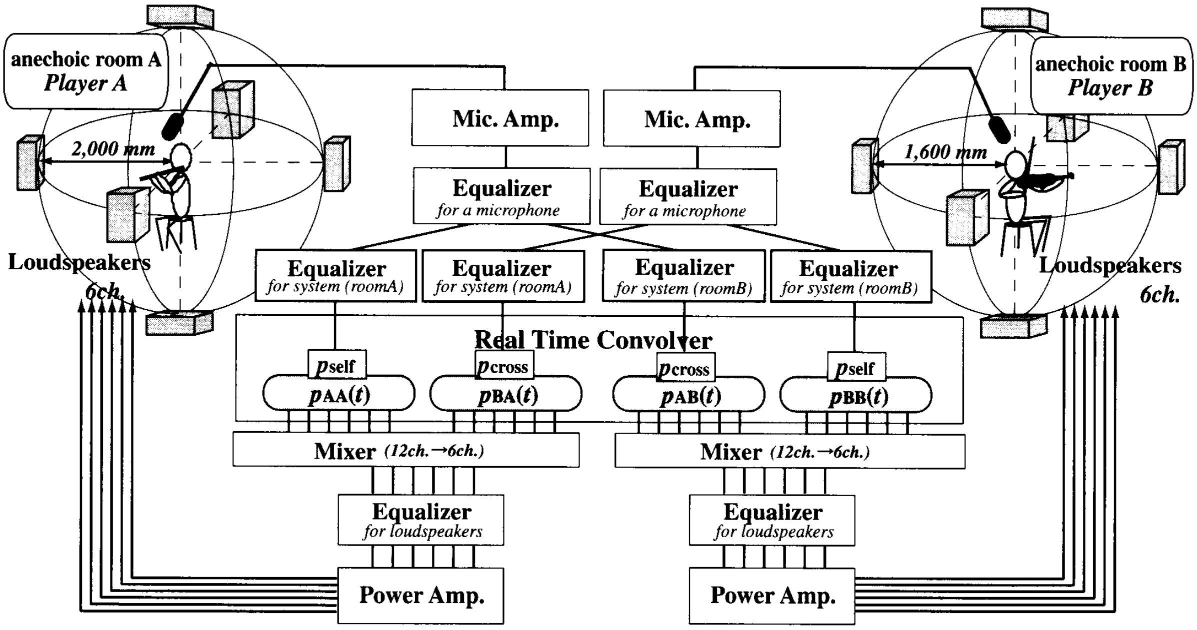


Fig. 5 Sound field simulation in two anechoic rooms.

Table 2 Experimental conditions measured in anechoic rooms.

(a) anechoic room A (condition for the subject)

Parameters	Condition	P_{self}			P_{cross}			
		L_{ER} [dB]	RT [s]	L_{Rev}[dB]	L_{ER}[dB]	RT [s]	L_{Rev}[dB]	EEL [dB]
Magnitude of ER	**ER1**	**−23.5**	1.75	−20.7	**−22.6**	1.75	−19.8	−16.0
	ER2	**−20.4**	1.65	−20.6	**−19.7**	1.75	−19.7	−15.5
	ER3	**−17.7**	1.68	−20.3	**−16.7**	1.75	−19.5	−14.6
RT	**RT1**	−20.4	**1.32**	−20.4	−19.7	**1.41**	−19.6	−15.5
	RT2	−20.4	**1.65**	−20.6	−19.7	**1.75**	−19.7	−15.5
	RT3	−20.4	**2.16**	−20.6	−19.6	**2.16**	−19.6	−15.5
Magnitude of Rev	**Rev1**	−20.4	1.66	**−23.4**	−19.7	1.76	**−22.4**	−15.5
	Rev2	−20.4	1.65	**−20.6**	−19.7	1.75	**−19.7**	−15.5
	Rev3	−20.4	1.75	**−17.6**	−19.7	1.79	**−17.1**	−15.5

(b) anechoic room B (condition for the co-player)

Parameters	Condition	P_{self}			P_{cross}			
		L_{ER} [dB]	RT [s]	L_{Rev}[dB]	L_{ER}[dB]	RT [s]	L_{Rev}[dB]	EEL [dB]
Magnitude of ER	**ER1**	**−21.8**	1.87	−19.8	**−22.7**	1.75	−20.6	−13.5
	ER2	**−19.2**	1.87	−19.7	**−19.8**	1.75	−20.5	−13.1
	ER3	**−16.5**	1.86	−19.4	**−16.9**	1.75	−20.2	−12.5
RT	**RT1**	−19.3	**1.43**	−19.7	−19.9	**1.36**	−20.4	−13.1
	RT2	−19.2	**1.87**	−19.7	−19.8	**1.75**	−20.5	−13.1
	RT3	−19.3	**2.22**	−20.0	−19.9	**2.07**	−20.4	−13.1
Magnitude of Rev	**Rev1**	−19.3	1.87	**−20.7**	−19.8	1.72	**−23.3**	−13.1
	Rev2	−19.2	1.87	**−19.7**	−19.8	1.75	**−20.5**	−13.1
	Rev3	−19.3	1.89	**−14.8**	−19.9	1.76	**−17.5**	−13.1

4. SUBJECTIVE EXPERIMENT

A series of subjective experiments was performed using the sound field simulation technique mentioned above. From the results, the relationships between acoustic conditions on a stage and the musicians' subjective impression were examined.

4.1. Requirements for Chamber Music Performance

In advance of the experiment, the subjective aspects to evaluate the acoustic conditions perceived in chamber music performance were investigated by interview survey. Fourteen professional musicians who participated in the experiment were asked to describe acoustic factors required for the performance of chamber music through conversation with the experimenter. The aim of this procedure is not only for the experimenters (the authors) to understand the musicians' keywords but also for the musicians themselves to become conscious of their perception in words because it is not necessarily needed for them to put the auditory perception into words in their usual activities.

From the comments made by the musicians during the interview, a lot of keywords were picked up and they were summarized through discussion with the musicians. As a result, it has been found that the following two factors are essential for almost all of the musicians.

Hearing each other. In order to communicate with the co-player and to understand the intention to create music together, delicate nuance of the tone and musical expression should be heard clearly. To satisfy this requirement, both of the player's own sound and the co-player's one need to be properly heard. This condition is important to keep balance between the instruments, to synchronize the performance, to make the melody conspicuous and so on. In the case where this condition is not satisfied, players complains by such expressions as "the sound is not heard," "the sound is too mixed," "there is time delay" or "the co-players is far."

Making harmony. In ensemble performance, the sounds made by different instruments need to be in harmony. At the same time, each sound needs to be properly separated. If these conditions are satisfied, musicians say "the sound is merged" or "the sound is united" and if not satisfied, they say "the sound is separated" or "the sound is scattering."

4.2. Test Procedures

Eight string instrument musicians (four violinists, three violist and one cellist) and six wind instrument musicians (three flutists, two oboists and one clarinet player) participated in this experiment as the subjects and they played in room A. An amateur violin player with 17 years' experience played the role of the co-player in room B. As an exception, a violinist and a violist made a pair for the ensemble and each played the part of co-player alternately. The subject sat at the center point in the simulated sound field (room A) and performed some phrases in a piece with the co-player in the other room (room B) by imaging they were playing on a real stage. In advance of the experiment, the subject made arrangements with the co-player about the piece for performance, each function in ensemble, length of the performance and so on. The sight of the other player was presented with a video-display set in each room.

After the performance under each experimental condition, the subject was asked to describe and judge his/her auditory impression of each experimental condition on such points as "hearing each other," "making harmony," characteristics of reverberation, and ease of ensemble performance. In addition, after the experiments for each series of conditions (ER1 to ER3, RT1 to RT3 and Rev1 to Rev3, respectively), the subject was asked to compare the three conditions for each parameter, to make comments on the difference of the conditions and to rank the conditions from a viewpoint of ease of chamber music performance. During the experiment, the experimenter also stayed in the anechoic room (room A) and asked the subject's response by direct conversation.

4.3. Experimental Results

During the experiment, it was observed that the subjects could concentrate on the performance with the co-player and judge the differences among the experimental conditions. Table 3 shows the summary of the comments made by the subjects, in which the number in the parenthesis indicates the number of response. Fig. 6 shows the results of the ranking among the three conditions for each variation regarding ER, RT and Rev. Horizontal axis of the figures shows the number of response.

As was expected beforehand, the effect of the order of presentation was observed in the results. For example, ER2, RT2 and Rev2 are the same condition (see Table 2) but different comments were given to them. This might be because the subjects compared the conditions for each variation subconsciously and figured out the difference among the conditions. Nevertheless, the following tendencies have been observed in the results.

Magnitude of early reflections. When the level of the early reflections was changed (from ER1 to ER3), it was observed that ease to hear the co-player's sound changed. From the comment of the subjects, it can be seen that most subjects felt difficulties of hearing the co-player's sound in the weakest condition (ER1) and they felt easier to hear the co-player's sound when the early reflections became stronger (ER2). However, in the case of the strongest condition (ER3), their responses split into two; six subjects judged the condition preferable because the co-player's sound became further easier to hear and six subjects judged it negatively on the point that the co-player's sound was too reverberant and too loud.

Reverberation time. In the comments made by the subjects, any clear tendency has not been found for the difference of reverberation time though it was observed that the subjects sensed the change/increase of reverberation. Regarding ease to hear the co-player, it seems that the increase of the reverberation time was not disturbing so much. Even under the longest reverberation time condition

Table 3 The summary of the comments made by the subjects.

Variation of the strength of early reflections	Variation of reverberation time	Variation of the strength of reverberation
ER1: *The co-player's sound is far. (9) *Difficult to hear the co-player's sound. (6) *Balance of sound of myself and of co-player is bad. (4) *The sound (reverberation) is agreeable and natural. (7)	RT1: *Easy to hear the co-player's sound. (7) *Not easy to hear the co-player's sound. (5) *The sound is not blended. (3) *Reverberation is not sufficient. (4) *The sound is hard. (2) *Not comfortable. (3)	Rev1: *Like in a small room. (8) *Difficult to make harmony. (6) *Easy to hear the co-player's sound. (5) *Not easy to hear the co-player's sound. (5) *Reverberation is not helpful to play. (6) *Reverberation is poor. (4) *More reverberation is desired. (4)
ER2: *The co-player's sound became easy to hear. (11) *The co-player's sound became closer. (7) *Balance of sound of myself and of co-player became better. (5) *The sounds are more natural than in ER1. (2) *Reverberation increased. (3)	RT2: *Easy to hear the co-player's sound. (6) *Not easy to hear the co-player's sound. (4) *The sound is more blended and easy to make harmony. (3) *Reverberation increased. (3) *Too reverberant. (4) *Reverberation condition is good. (2) *Balance of sound of myself and of co-player became better. (2)	Rev2: *It became easier to make harmony. (9) *Sound is merged and it is easy to make harmony. (4) *More pleasant to play. (6) *Easy to hear the co-player's sound. (8) *Not easy to hear the co-player's sound. (5) *The co-player's sound is far. (4) *Balance of sound of myself and of co-player is good. (2) *Reverberation increased. (4) *Too reverberant. (2)
ER3: *The co-player's sound became easy to hear. (6) *The sound is too reverberant and too loud. (6)	RT3: *Easy to hear the co-player's sound. (7) *Reverberation is loud. (5) *Reverberation increased. (3) *Difficult to hear the co-player's sound and to play together because of reverberation. (2) *The sounds are well blended and easy to make harmony. (3)	Rev3: *Difficult to hear the co-player's sound. (7) *Easy to hear the co-player's sound. (4) *Not easier to make harmony than Rev2. (5) *Difficult to make harmony. The sound is too mixed and muddy. (2) *Easy to make harmony. (2) *Too reverberant. (3) *Pleasant to play. (3)
Comparisons among the three conditions for each variation		
*Ease to hear the co-player's sound changed. (10) *The distance to the co-player changed. (7) *Reverberation increased. (6)	*Reverberation increased/changed. (7) *All conditions have both of favorable and unfavorable aspects. (5) *Differences among three conditions were small. (3) *Ease to make harmony changed. (2)	*Reverberation increased. (12) *The size of the stage became larger. (3) *The three conditions are clearly different. (11)

(RT3), only two subjects mentioned the disturbance of the reverberation while seven subjects commented that it was easy to hear the co-player's sound. As shown in Fig. 6, the number of the first ranking is the biggest for the longest reverberation time condition (RT3) for both of the string instrument and wind instrument players.

Magnitude of reverberation. As the experimental condition was changed in due order from Rev1 to Rev3, most of the subjects commented that the reverberation had increased. A tendency was also seen that the magnitude of the reverberation relates to both impression of ease to hear the co-player and that of making harmony. Under the weakest reverberation condition (Rev1), many subjects commented that they felt as playing in a small room. They judged that this condition was not suitable for chamber music because the reverberation was too poor and it was difficult to make harmony. When the magnitude of reverberation increased (Rev2), the tendency was observed that the subjects became more satisfied in ease of "making harmony." However, under the strongest reverberation condition (Rev3), several subjects made such negative comments as "difficult to hear the co-player's sound," "difficult to make harmony," "too reverberant," and "too mixed and muddy." To see the result of ranking shown in Fig. 6, it is seen that the conditions satisfying the requirements of "hearing each other" and "making harmony" were highly evaluated and the condition Rev2 or Rev3 was more preferred than the condition Rev1.

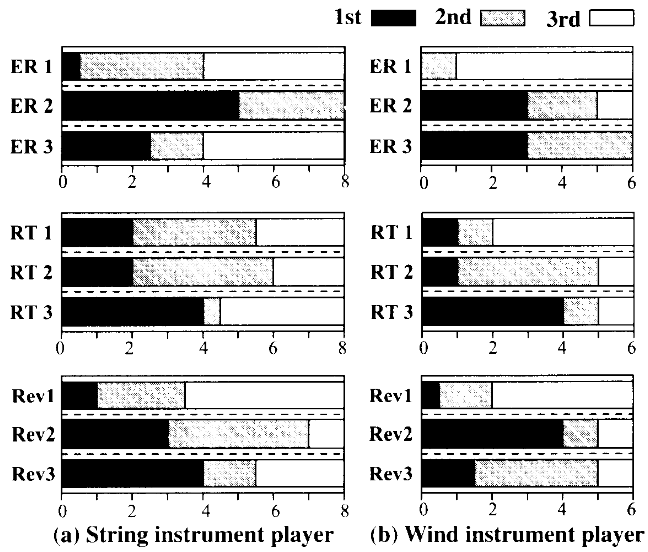


Fig. 6 The results of the ranking on ease of chamber music performance (When two conditions were chosen as the same rank, 0.5 was given to the two conditions evenly).

4.4. Discussions

In the previous studies [2,4], it was suggested that the early reflection is important to hear each other and this suggestion has been reaffirmed in this experiment. For the evaluation of the magnitude of the early reflections, Gade proposed *EEL* as a parameter related to "hearing each other" in ensemble performance [4,8]. However, the variation of this parameter was only within 1.4 dB in this experiment (see Table 2) and its validity could not been confirmed in the case of ensemble performance between relatively close positions as set in this study. Regarding the strength of the early reflections, not a few musicians pointed out that the weaker condition was preferable from a viewpoint of the reverberation quality (hall sound), which is the same finding as in our previous study for solo performance [1]. On the other hand, the stronger condition of early reflection was generally evaluated from the viewpoint of "hearing each other" in this experiment.

Regarding the effect of reverberation, Gade suggested that it has a negative influence on the requirement of hearing each other [4]. This tendency was observed under the strongest reverberation condition (Rev3) in this experiment. However, it has been found that the reverberation is much related to the requirement for making harmony and proper amount of reverberation is necessary for chamber music performance. As a result of this study, it has been suggested that the energy of reverberation is more important than the reverberation time for musicians.

As for the reliability of the results of this study, it is difficult to apply the conventional statistical methods to the experimental results because the subjective judgments in this kind of study are closely related to musician's background and intension in performance and the judgments could not be made as the simple response to the stimuli [9]. However, the tendencies of the judgments obtained in this study were almost consistent with the results of our previous experiment [7].

5. CONCLUSIONS

In order to simulate the 3-dimensional sound field on the stage of a concert hall, a technique using 24 channel digital convolution system and two anechoic rooms was devised and a subjective experiment on ensemble performance of chamber music was carried out with the participation of professional musicians. In the results of this experiment, the following tendencies have been observed on the relationships between the transient acoustic properties of the sound field and players' subjective impression.

- The early reflections increase ease of hearing the co-player's sound, whereas they can cause excess loudness of the co-player's sound in the case where they are too strong.
- In ensemble performance, musicians are not so sensitive to the change of reverberation time but rather more conscious of the magnitude of the reverberation. It has been clearly found that this factor is much related to ease of "hearing each other" and "making harmony."

In the previous studies on ensemble performance, which were made mainly for orchestra performance, the easiness of "hearing each other" was regarded as the most important factor and the effect of the early reflections was firstly esteemed. From the results of this study focusing on chamber music performance, however, it has been found that ease of "making harmony" is also essential as well as "hearing each other" and musicians require both of these conditions at the same time. In order to realize these players' requirements, not only the early reflections but also the reverberation should be in optimum strength.

As another investigation for ease of ensemble performance, the authors conducted an experiment focusing on the conditions for two distant performers in orchestra [10]. In the experiment the same simulation system were used and the experimental conditions were prepared to simulate distant positions. This experiment will be presented in the future.

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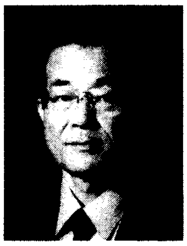

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