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A consideration on acoustic properties on concert-hall stages

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ABSTRACT

This paper discusses acoustic properties that musicians experience on a concert hall stage; the discussion is based on the authors' experience gained from conducting experimental studies using a three-dimensional sound field simulation technique. First, the experimental findings on the relationship between the acoustic requirements of musicians and acoustic conditions such as early reflection and reverberation are reviewed. Second, the validity and problems of stage acoustic indices ST_{early}, ST_{late}, and *EEL* are addressed. In addition, unsolved issues with regard to musicians' requirements during their performance are considered and problems requiring future study are pointed out.

INTRODUCTION

The effects of a room's acoustical conditions on musicians on stage can be effectively investigated by performing laboratory experiments in which these conditions can be changed freely and quickly. In order to make subjects feel that they are virtually playing on real stage, we developed a sound field simulation system that employs a 6-channel recording/reproduction technique. Using this simulation system, experimental studies were conducted to find the relationship between physical parameters and musicians' psychological evaluation in terms of solo performance [1], ensemble performance with two players in a chamber music performance [2], and two players in an orchestral performance [3].

This paper provides a summary of our experimental studies that consider stage acoustic properties in terms of sounds that musicians find useful and detrimental. Experimental results that have previously been published/presented are briefly reviewed. Based on this review, the validity and problems of stage acoustic indices and aspects of stage acoustics requiring future study are considered.

OUTLINE OF METHOD OF OUR STUDY

In order to examine the problems that can arise in actual concert halls and to investigate musicians' requirements during their performance in concerts, we have been focussing on improving the similarity of our laboratory conditions to the actual ones. Our study consists of field measurement, construction of a sound simulation system, analysis of acoustical properties, examination of an experimental parameter, interview survey on musicians' requirements, and the development of a subjective test procedure.

Field measurement

Acoustic measurements in concert halls were performed in order to examine the acoustic properties that musicians experience on concert-hall stages and to obtain the impulse responses that were used in the sound field simulation.

The measurement points were chosen so as to represent the relationship between two players and their musical instruments, as shown in Figure 1. To obtain the sound transmission properties experienced by the two players on a stage, A and B, four transmission paths, $p_{\mathrm{AA}}(t)$, $p_{\mathrm{BB}}(t)$, $p_{\mathrm{AB}}(t)$, and $p_{\mathrm{BA}}(t)$, were assumed, as shown in Figure 1. Here, $p_{\mathrm{AA}}(t)$ and $p_{\mathrm{BB}}(t)$ (which together are denoted by $p_{\mathrm{self}}(t)$) are the sound transmission characteristics from the musical instrument of player A/B to player A/B, respectively, and $p_{\mathrm{AB}}(t)$ and $p_{\mathrm{BA}}(t)$ (which together are denoted by $p_{\mathrm{cross}}(t)$) are those from the musical instrument of player A/B to the player B/A, respectively. In the case of solo performances, only $p_{\mathrm{self}}(t)$ was measured.

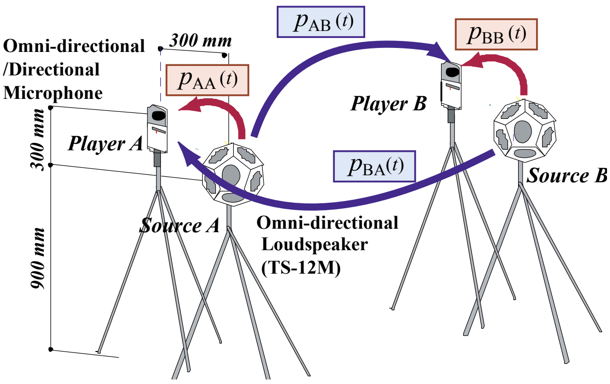


Figure 1. Configuration of measurement instruments

For our measurements, a dodecahedral loudspeaker was used to model the musical instruments and an omni-directional or uni-directional microphone (Sony C48) with cardioid directivity was located just behind the sound source. In measurements using the uni-directional microphone, the directional impulse responses in six orthogonal directions were measured by rotating the microphone in 90° increments and these responses were used for the sound field simulation. The omni-directional impulse responses were analysed in order to investigate the stage's acoustic properties.

In order to examine the acoustic properties of concert halls, we fixed the distance between two players for the case of chamber music and of orchestra. Figure 2 shows the measurements positions of these two cases. The case of orchestra examines ensemble performance by two musicians in distsnt positions.

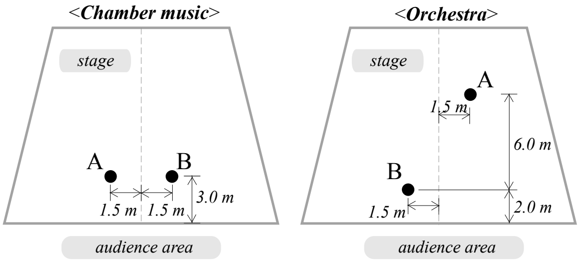


Figure 2. Measurement points for ensemble performance

Sound field simulation system

The acoustic conditions of an ensemble performance by two players on a concert hall stage were simulated using the system illustrated in Figure 3. That is, the 6-channel directional impulse responses measured in actual concert 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: 7 m^3 and room-B: 4.0 × 6.8× 7.0 m) were coupled acoustically, and the four sets of 6-channel directional impulse responses installed in the digital convolution system (24 channels 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 by a uni-directional microphone (Sony, C48) set at a point close to each player in each room. The signals were convolved with the 6-channel directional impulse responses for $p_{\mathrm{self}}(t)$ and for $p_{\mathrm{cross}}(t)$, respectively, using a 24-channel real-time digital convolution system. In the case of $p_{\mathrm{self}}(t)$, 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 $p_{\mathrm{self}}(t)$ and $p_{\mathrm{cross}}(t)$ were mixed for each channel and reproduced through the six loudspeakers (TANNOY, T12) arranged in each room. For the case of solo performance, the convolution system for $p_{\mathrm{AA}}(t)$ (6-channel) was activated.

The applicability of this simulation system to psychoacoustic experimentation was examined by performing a preliminary subjective experiment on a solo performance [1] and an ensemble performance [4]. The results of this investigation confirmed that the musicians could get a feeling for the acoustic reality of performing on a real stage and could distinguish differences in acoustic conditions.

Acoustic properties

To analyze the transient process, the impulse responses measured through an omni-directional microphone were divided into three components, as shown in Figure 4: the direct sound including the reflection from the floor (Dir), the early reflections (ERs), and the reverberation process (Rev). These components of an impulse response were separated in the time domain and the energy (squared and integrated sound pressure) of the respective components were calculated and expressed in levels [4]. Here, the energy level of the early reflections and that of the reverberation process were indicated as a level relative to the direct sound of $p_{\mathrm{self}}(t)$; L_{ER} and L_{Rev}, respectively. The L_{ER} and L_{Rev} values of $p_{\mathrm{self}}(t)$ correspond to ST_{Early} and ST_{late}, respectively, except that they are 7 dB lower than the ST values because of the difference in the distance between the sound source and the microphone.

In addition, RT was read from the later part of the impulse responses, which excluded the effect of the direct sound and early reflections. The indices were calculated for the middle frequency range in two octave bands, including the 500 Hz and 1 kHz bands.

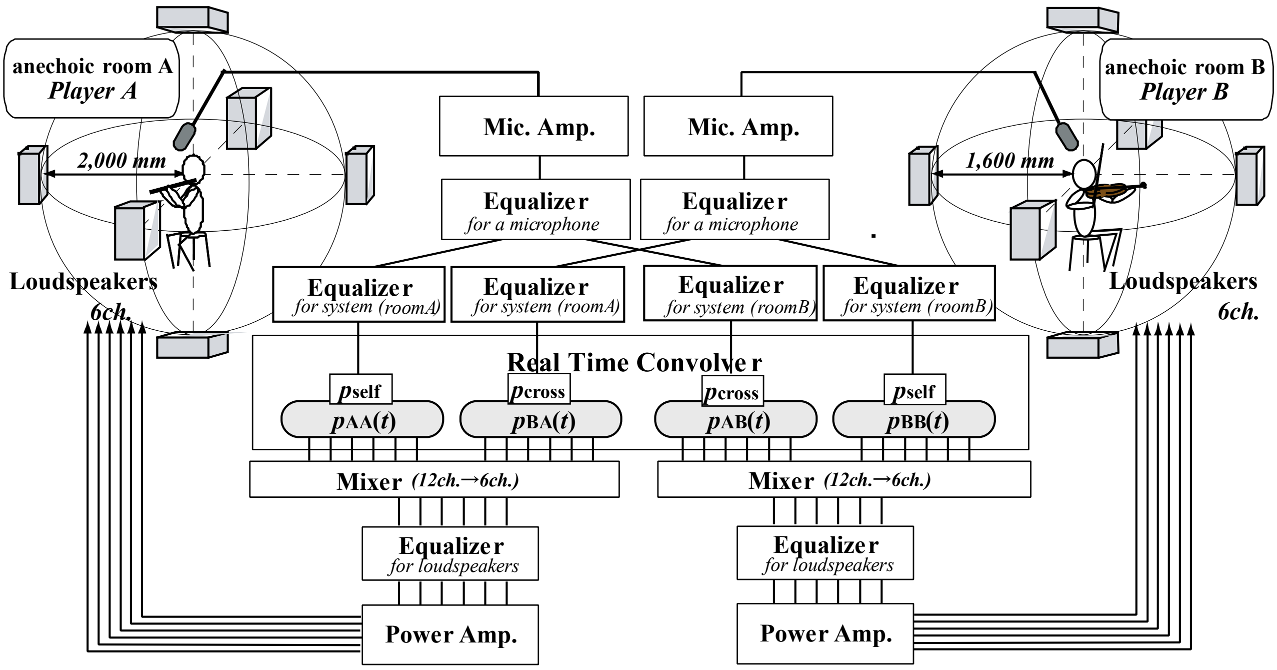


Figure 3. Sound field simulation for stage acoustics

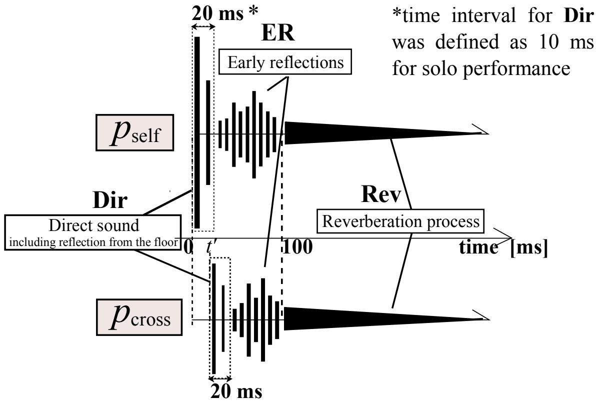


Figure 4. Separation of impulse responses

Experimental parameter

In the subjective experiment for ensemble performance, three parameters were changed: the magnitude of the early reflections (L_{ER}), reverberation time (RT), and magnitude of the reverberation process (L_{Rev}). Each parameter was changed in three steps, as indicated in Table 1 (see Figures 5, 6, and 7). The variation ranges and values of these parameters were determined by referring to measurement results from actual concert halls [1-3]. For all conditions, the component of direct sound that is included in $p_{\mathrm{cross}}(t)$ 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, $p_{\mathrm{self}}(t)$ and $p_{\mathrm{cross}}(t)$ were measured at the centre point of each simulated sound field, using the same set-up as shown in Figure 1, in which an omni-directional microphone was used and the experimental parameters (L_{ER}, RT, L_{Rev}) were measured.

In the subjective experiment for solo performance, the effect of late reflection (LR), which is sometimes observed after a considerably long delay in large concert halls, was examined. To simulate late reflection, a relatively distinct late reflection measured in a concert hall was sampled by multiplying an envelope function and using this reflection as a filter coefficient of the real time convolution system [1]. The convolved signal was generated from a loudspeaker set in front of the performer. The conditions of LR together with L_{ER} and RT were set in a solo performance experiment (see Table 1). In this case, $p_{\mathrm{self}}(t)$ at the centre point of the simulated sound field were measured to set the experimental conditions.

Table 1. Experimental parameters*1

Parameter/ condition ID		solo	ensemble	
			chamber music	orchestra
L_{ER}*2	ER1 to 3	-21±3 dB	-20±3 dB	-22±3 dB
RT	RT1 to 3	1.9±0.3 sec	1.7±0.4 sec	2.0±0.4 sec
L_{Rev}	Rev1 to 3	-	-20±3 dB	-22±3 dB
LR	LR1 to 3	3 steps*3	-	-

*1: The table list approximate values. Accurate data were indicated in [1-3]

*2: In the solo experiment, the conditions for L_{ER} were presented sequentially from a stronger condition to a weaker condition. In the ensemble experiment, they were presented from a weaker condition to a stronger condition (as indicated by the arrow in Figures 5, 6, and 7).

*3: The levels of the late reflection were adjusted as follows: LR1 (None): a condition with no late reflection; LR2: a condition in which the late reflection was faintly audible when an impulsive sound was generated; LR3: a condition in which the reflection was clearly audible. Delay time of the LR was fixed at 250 ms.

Musicians' requirements

In advance of each experiment, the musicians' requirements and the key criteria they use to evaluate the acoustic conditions perceived in a performance were investigated in an interview survey [1][2].

The professional musicians who participated in the experiment were asked to describe these acoustic factors in an interview. The aim of this procedure was not only for the experimenters (the authors) to understand the musicians' keywords, but also for the musicians themselves to become aware of their perceptions in words, since their daily performance activity does not necessarily require them to articulate their auditory perceptions [5].

Test procedure

In the subjective experiment, the subject sat at the centre point of the simulated sound field (room A) and performed arbitrary phrases while imagining that he/she was playing on a real stage. In the ensemble experiments, the subject would perform a number of phrases from a piece along with a co-player, an amateur violinist with 17 years of experience, who sat in the other room (room B). The two players could see one another via video-display sets that were placed in both rooms.

After the performance under each experimental condition, the subject was asked to describe and evaluate his/her auditory impression of each experimental condition in terms of such criteria as their prior requirements for each performance style, reverberation characteristics, and ease of performance. In addition, after the experiments for each series of conditions (ER1 to ER3, RT1 to RT3 and Rev1 to Rev3, LR1 to LR3, respectively), the subject was asked to compare the three conditions for each parameter, to make comments on the differences in the conditions, and to rank the conditions in terms of ease of performance. In addition, during the experiment, the experimenter stayed in the anechoic room (room A) and asked the subject for selected responses in direct conversation.

EXPERIMENTAL RESULTS FOR SOLO PERFORMANCE

In the solo experiment, the 6-channel directional impulse responses measured in an arena-type concert hall with 1,702 seats, 17,800 m^3 volume, and a 2.3 s reverberation time in the mid-frequencies were used as the standard room impulse response signals. By modifying the impulse responses, nine conditions were set (Table 1) [1]. The subjective tests were performed with twelve professional musicians: six stringed instrument musicians (three violinists and three violists) and six wind instrument musicians (three flutists, two oboists, and one clarinet player).

Figure 5 shows the number of players who chose each condition as the best among the three steps. When two conditions were chosen as the best, an equal value of 0.5 was assigned to the two conditions. The players' comments were also arranged into a table for consideration [1]. In the results, the following tendencies were found.

Magnitude of early reflections

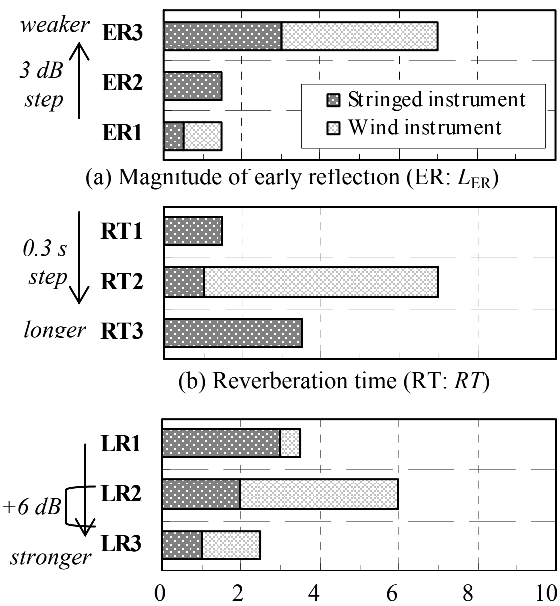
When the level of early reflection was changed, the subjective impression of spatial size changed. That is, the stronger the early reflection, the smaller the spatial size that was sensed. This observation was common among the wind instrument players. Several stringed instrument players commented that the sound field felt more reverberant when the early reflection was weaker. It should also be noted that there were a few subjects who commented that the differences between the experimental conditions were so subtle that they could not be evaluated. Generally, the weakest condition of the early reflection ER3 was the most preferred.

Reverberation time

All the wind instrument players preferred the reverberation condition RT2 (1.9 s). Their general comments were as follows: if the reverberation is shorter than that, it is not sufficient to enable them feel the effect of the hall, while if the reverberation is longer than that, it may be disturbing, especially in terms of their hearing each other in ensemble performance. In the case of the stringed instrument players, they tended to prefer the longer reverberation condition (RT3, 2.2 s), although several subjects commented that under this condition, the reverberation might make it difficult for them to hear each other in ensemble performance. There was also a tendency for differences in the reverberation condition to make the players sense a difference in the spatial size (room volume) of the hall. That is, a longer reverberation time made the players feel that the room had a larger volume.

Magnitude of late reflection

Concerning late reflection, all the wind instrument players preferred conditions LR2 and LR3, under which the late reflection was audible, to the condition LR1 (without reflection). The subjects commented that these conditions with audible late reflection made them feel at ease and/or feel that they could convey detailed expression to the audience. Such a tendency was not clearly found in the results for the stringed instrument players. Among them, three subjects preferred the conditions LR2 and LR3 because he/she felt that the sound projected well into the audience area or that it is easy to add nuance, whereas three subjects preferred the condition without late reflection.



(a) Magnitude of early reflection (ER: L_{ER})

(b) Reverberation time (RT: RT)

(c) Magnitude of late reflection (LR)

Figure 5. Results of solo performance experiment.

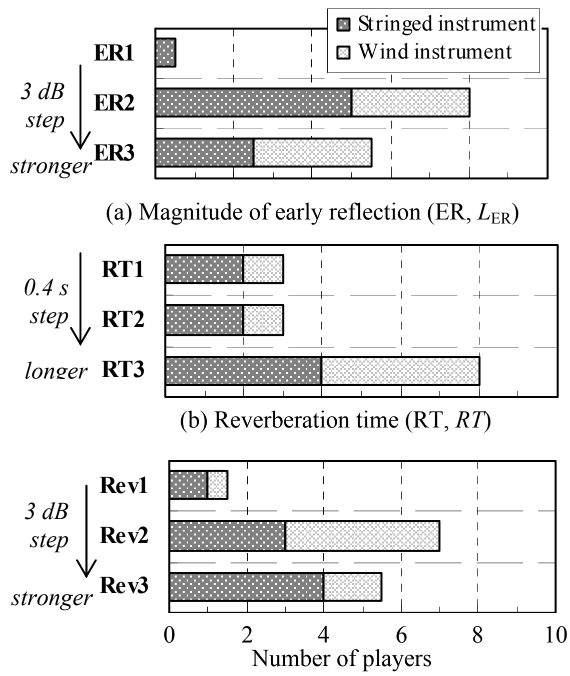
EXPERIMENTAL RESULTS FOR ENSEMBLE PERFORMANCE OF CHAMBER MUSIC

The 24-channel directional impulse responses measured in a shoebox-type concert hall with 440 seats, 4,228 m^3 volume, and a 1.8 s reverberation time in the mid-frequencies were used as the standard room impulse response signals. By modifying the impulse responses, nine conditions (Table 1) were set. Subjective tests involving 14 professional musicians were performed: eight stringed instrument musicians (four violinists, three violists, and one cellist) and six wind instrument musicians (three flutists, two oboists, and one clarinet player).

Table 2 presents a summary of the comments the subjects made when comparing the conditions for each parameter; the numbers in parentheses indicate the number of responses. Figure 6 shows the number of players who chose each condition as the best among the three steps. When two conditions were chosen as the best, an equal value of 0.5 was assigned to the two conditions. The players' comments were also arranged into a table for consideration [2]. In the results, the following tendencies were found.

Table 2. Comments comparing the three steps of each parameter made by subjects in chamber music experiment

ER	-Ease of hearing co-player's sound changed. (10) -Distance to co-player seemed to change. (7) -Reverberation increased. (6)
RT	-Reverberation increased/changed. (7) -All conditions have both of favourable and unfavorable aspects. (5) -Differences among three conditions were small. (3) -Ease of making harmony changed. (2)
Rev	-Reverberation increased. (12) -Size of the stage seemed larger. (3) -The three conditions are clearly different. (11)



(a) Magnitude of early reflection (ER, L_{ER})

(b) Reverberation time (RT, RT)

(c) Magnitude of reverberation (Rev, L_{Rev})

Figure 6. Results of ensemble experiment for chamber music.

Magnitude of early reflections

When the level of early reflections was changed (from ER1 to ER3), a change was observed in the ease with which co-players heard each other. The subjects' comments indicated that most of them had difficulty hearing their co-player's sound in the weakest condition (ER1), and they found it easier to hear their co-player's sound when the early reflections became stronger (ER2). However, in the case of the strongest condition (ER3), their responses were split: six subjects found the condition preferable because the co-player's sound became even easier to hear, and six subjects judged it negatively, finding the co-player's sound too loud and reverberant.

Reverberation time

In the subjects' comments, no clear tendency was found for the difference in reverberation time, though it was observed that the subjects did sense the change/increase of reverberation. Regarding ease of hearing their co-players, an increase in the reverberation time did not seem too disturbing. Even under the condition of the longest reverberation time (RT3), only two subjects mentioned being disturbed by the reverberation, while seven subjects commented that it was easy to hear their co-player's sound. As shown in Figure 6, the number of the best preferred was the largest for the longest reverberation time condition (RT3), for both the stringed 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 for the magnitude of reverberation to be related to both an impression of ease in hearing one's co-player, and ease in creating harmony. Under the weakest reverberation condition (Rev1), many subjects commented that they felt as if they were playing in a small room. They felt that this condition was unsuitable for chamber music because the reverberation was too poor and it was difficult to create harmony. When the magnitude of reverberation increased (Rev2), the tendency was observed for subjects to become more satisfied by the ease with which they could create 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'. As a whole, it can be seen that the conditions that satisfied the players' requirements of 'hearing each other' and 'making harmony' were highly evaluated, and conditions Rev2 or Rev3 were preferable to condition Rev1.

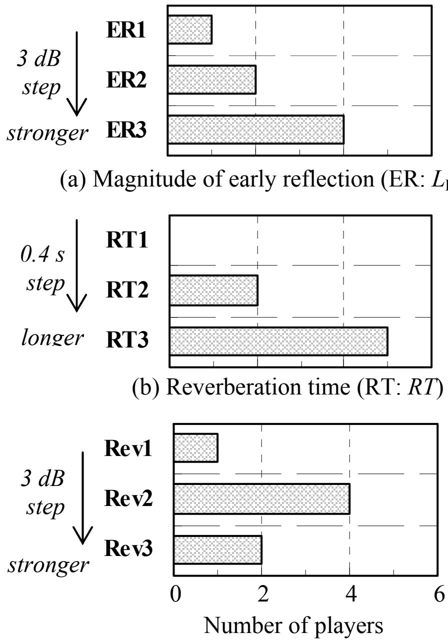
EXPERIMENTAL RESULTS FOR ENSEMBLE PERFORMANCE FOR ORCHESTRA

The 24-channel directional impulse responses measured in a shoebox-type concert hall with 2,020 seats, 22,776 m^3 volume, and a 2.4 s reverberation time in the mid-frequencies were used as the standard room impulse response signals. By modifying the impulse responses, nine conditions (Table 1) were set. Subjective tests involving seven professional wind instrument musicians (three flutists, two oboists, and two clarinet players) were performed.

Table 3 presents a summary of the comments subjects made comparing the conditions for each parameter, in which the numbers in parentheses indicate the number of responses. Figure 7 shows the number of players who chose each condition as the best among the three steps. When two conditions were chosen as the best, an equal value of 0.5 was assigned to the two conditions. Players' comments were also arranged into a table for consideration [3]. In the results, the following tendencies were found.

Table 3. Comments comparing the three steps of each parameter made by subjects in orchestra experiment

ER	-It became easier to listen to the sound by degrees. (4) -Though the sound level increased, it was not helpful to playing in an ensemble. (2)
RT	-The reverberation changed. (5) -The co-player's sound changed. (3)
Rev	-Reverberation increased. (6) -The three conditions are clearly different. (5)



(a) Magnitude of early reflection (ER: L_{ER})

(b) Reverberation time (RT: RT)

(c) Magnitude of reverberation (Rev: L_{Rev})

Figure 7. Results of ensemble experiment for orchestra.

Magnitude of early reflections

The magnitude of early reflections is related to how clearly the sound is heard. When there are more early reflections, the sound was considered to be louder and clearer, though a few musicians pointed out that this was not necessarily helpful to playing in an ensemble.

Reverberation time

The condition with longer reverberation was preferred because reverberation is considered helpful to music-making. In all cases, most of the subjects commented that the sound of the co-player was easily heard, though a few musicians pointed that it became difficult to hear the sound in detail under the longest reverberation condition, RT3.

Magnitude of reverberation

The middle condition of the magnitude of the reverberation, Rev2, was most preferred. In the case of Rev3, the musicians' requirements in terms of hearing each other were not satisfied due to excessive reverberation.

DISCUSSION

Summary of the findings

In the design of stage acoustics, early reflection is generally taken into account, and previous studies [6-8] have suggested that early reflection is an important factor in musicians' ability to hear each other. This observation was reexamined in this experiment when the strength of early reflection was changed in steps. In solo settings, differences in the strength of early reflection were judged to be changes in spatial size by most of the wind instrument players, and a weaker level of early reflection tended to be preferred. In the ensemble settings, not a few musicians pointed out that the weaker condition was preferable from the viewpoint of reverberation quality (hall sound); however, the stronger condition of early reflection was generally evaluated from the viewpoint of 'hearing each other'. These facts indicate that early reflection is related to musicians' sense of the quality of reverberation (especially as related to spatial image) and the ease with which they can hear each other.

Regarding the other types of reflections, we focused on the effect of late reflection, which involved a considerably long delay time from the rear wall of the audience area [8]. By changing the strength of this reflection in the solo experiment, it was shown that late reflection was not necessarily considered disturbing, was even considered rather favourable at a proper degree of strength. According to the musicians' comments, they can feel the sound propagating to the audience area when they sense that the late reflection is moderate. Consequently, it has been suggested that musicians can feel that a kind of 'support' is given them by late reflection.

Regarding the effect of reverberation, Gade suggested that it has a negative influence on musicians' requirements in regard to hearing each other [7]. In this study, the effect of reverberation time was examined in both the solo experiment and ensemble experiments. In addition, the effect of the magnitude of reverberation was tested in the ensemble experiments. As a whole, it was indicated that reverberation has a positive effect on the ability of co-players to create harmony, which is especially important in chamber music, and it has a negative influence on musicians' requirements for hearing each other. It has also been suggested that the energy of reverberation has a greater influence on musician's acoustic preferences than the reverberation time.

In previous studies and in the design of stage acoustics, the ease with which musicians can hear one and other was regarded as the most important factor, and the effect of early reflections was most highly esteemed. The results of this study, however, suggest that not just the level of early reflections but also that of the reverberation should be optimal in order to fulfil the requirements voiced by musicians.

Acoustic indices

ST proposed by Gade [7] is well known as an index for evaluating the strength of reflections or reverberation on stages. We have analysed *ST* in our investigations of stage acoustics and found the following validities and problems that merit discussion.

- *ST* is valid for evaluating differences in the energy of hall response by excluding direct sound, which is always dominant in impulse responses on stages.
- Since *ST* indicates the energy of reflections as a value relative to the energy of direct sound, this value was strongly affected by the measurement settings. Our setting (shown in Figure 1) gives a value that is about 7 dB lower than Gade's original setting, in which the distance between the sound source and receiver is 1 m. The rationale for our configuration is that we tried to measure acoustic conditions using the same method in both real halls and simulated fields, and 1 m was too long a distance to separate the equipment in the simulated sound field.
- In the calculation of ST_{early}, the starting point of the integration of the sound pressure of the early reflections must be determined in order to exclude the reflection from the stage floor and to include the main reflections from the walls. When considering the measurement points close to the stage reflectors, a period of 10 ms can be a reasonable point of compromise.
- When a short period such as 10 ms is set for calculation of the direct sound component, the procedure used to calculate the value may produce different results. That is, when the band-pass filtering precedes the time windowing, the time period cannot fully include the direct sound in the lower band, which has an impact on the *ST* value. In our analysis, the impulse responses measured for all frequencies were first divided in the time domain and filtered through band-pass filters. This procedure should be defined in order to make it possible to compare the values reported by different researchers.
- In recent studies, ST_{early}, which indicates the energy of early reflections (up to 100 ms), tends to be discussed mainly as a stage parameter. However, since our study suggests that the energy of reverberation has a considerable effect on the preferences of players, ST_{late}, which indicates the energy of reverberation (from 100 ms), should also be a focus of attention.
- *EEL* was proposed for an ensemble situation as a parameter related to the musicians' hearing of each other [7,9]. Since *EEL* calculates the energy of direct sound from the co-player's position with early reflections, the variation of *EEL* is small even if the strength of the early reflection changes considerably, especially when two co-players are positioned close to each other (say 3 m, [2]). In order to evaluate the early reflections determined by the stage condition, the direct sound from the co-player's position should be excluded, as in the calculation of ST_{early}.

Another finding of our study is that the late reflection from audience area has a considerable effect on musicians. However, the audibility of the late reflection cannot be evaluated by the *ST* values. This, too, is a point that merits further investigation.

CONSIDERATION OF FUTURE WORK

From the results of our studies mentioned above, it has been found that various problems still remain to be investigated on "stage acoustics". Among them, it is the most important problem to determine physical acoustic parameters which can well describe performers' subjective impression on stage related to the effect of early reflections, reverberation (not only reverberation time but also the volume of reverberation), the effect of late reflection from the audience area, etc. as mentioned in "DISCUSSION" part.

The conditions set in our studies introduced in this paper were limited and therefore a lot of problems remain to be investigated in the future. For example, it is known that an orchestral performance requires acoustics that permit the realization of the wide dynamic range of a full orchestra's sound. Further study is needed in order to determine the acoustic conditions required for these modes of music-making.

In a related topic, we have recently been studying how expert musicians adjust their performance to suit the acoustics of individual concert halls. Our study confirmed that these musicians adapt their performance to the acoustics of a given venue, and differences in their performance could indeed be objectively identified, at least in terms of the tempo and the extent of vibrato [10]. In light of this, undesirable acoustic properties that musicians can easily cover up by adjusting their playing would not be detrimental, whereas acoustic properties that are hard to compensate for would pose a serious problem. This flexibility of musicians offers yet another interesting perspective on stage acoustic properties.

Another concern of performance musicians might be how their performance sounds to the audience. In this context, the stage acoustic properties that enable musicians to predict the sound being produced in the audience area are quite important. By applying a 6-channel sound simulation system, a musician can listen to how his/her performance sounds in the audience area by convolving his/her dry music signal that was recorded during the stage acoustic experiment with the 6-channel impulse responses measured in the audience area. Our preliminary experiment using this technique evoked great enthusiasm from the musicians involved [11]. This topic can thus be further investigated to expand our vision of stage acoustics.

In the next stage of "stage acoustics", the ways to design architectural conditions of concert-hall stage should be reconsidered based on acoustical viewpoint. For this aim, the acoustic parameters related to "stage acoustics" should be established so that they could be checked not only in real sound field but also in virtual sound field under the design of concert halls.

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