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The role of reflections from behind the listener in spatial impression☆

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Abstract

This paper describes the results of two subjective experiments to clarify the role of reflections arriving from behind the listener in the perception of spatial impression. The experiments investigate the effects of reflections from behind the listener on both listener envelopment (LEV) and auditory source width (ASW) and which is more effective for LEV, the early or late reflections. The results of experiments clearly show that: (1) The listener can perceive LEV and ASW as two distinct senses of a sound image. (2) The role of reflections arriving from behind the listener is to increase LEV in spatial impression. Namely LEV increases as the relative reflection energy of sound arriving from behind the listener increases. (3) The early reflections also contributes to the perception of LEV, while (4) the late reflections are more effective for LEV than the early ones. However, it cannot be definitely concluded whether C_{80} affects LEV or not.

1. Introduction

The auditory sensations associated with the acoustics of a space can be divided into three groups. The first group concerns temporal attribute (rhythm, durability, reverberance, etc.). The second group involves the spatial one (direction, distance,

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spatial impression, etc.), while the third relates to the quality one (loudness, pitch, timbre, etc.) [1]. Among these sensations, it is well-known that spatial impression is one of the most important in concert halls. In this paper, the present authors define the term "spatial impression" as the spatial extent of the sound image. Of course, it is the more general overall concept, because they regard it as a multi-dimensional sense and they suppose it to correspond to the term "spatial impression" which Bradley and Soulodre use [2,3].

In 1989, Morimoto and Maekawa [4], demonstrated that spatial impression comprises at least two components by subjective experiments using a multidimensional analysis. One is auditory source width (ASW) which is defined as the width of a sound image fused temporally and spatially with the direct sound image and the other is listener envelopment (LEV) which is the degree of fullness of sound images around the listener, excluding a sound image composing ASW.

Before proceeding, the difference between our previous work and the present one in nomenclature for such spatial characteristics should be clarified. Morimoto and Maekawa [4] used the terms "broadening," "auditory spaciousness" and "envelopment," in place of such terms being used in the present paper as "spatial impression," "auditory source width" and "listener envelopment," respectively, though the definitions of each term used by Morimoto and Maekawa [4] are identical to those of the corresponding terms used in the present paper. It should, however, be noted that there were some reasons why Morimoto and Maekawa [4] did not use the same terminology as being used in the present paper, i.e. why they did not use "spatial impression" to address the general overall concept: Morimoto and Maekawa did not use this term to avoid possible confusion — the term "spatial impression" had already been used mainly to describe the source broadening produced by early lateral reflections. Besides, the abbreviation SI for "spatial impression" for this meaning had already been circulated: Barron [5] and Barron and Marshall [6] did not use the term "spatial impression" for the general overall concept, nor did they suppose that it is a multidimensional sense in their extensive and pioneering work. Barron used the term "spatial impression" for the sense of source broadening produced by early reflections. He stressed that early lateral reflections produced a very different impression from that produced by reverberation: reverberation was described as providing a certain degree of envelopment in the sound and giving an impression of distance from the source.

In 1995, Bradley and Soulodre [2] also confirmed that spatial impression in concert halls is composed of at least two distinct senses. The present authors believe that, generally speaking, the listener perceives not only one sound image fused temporally and spatially with the direct sound image based on the law of the first wave front, but also the other ones caused by reflections not affected by the law. Moreover, both sound images appear regardless of the delay times of reflections after the direct sound and each sound image has its own spatial extent.

Fig. 1 illustrates the concepts of the two types of spatial impression. Of course, ASW and LEV vary in terms of size and shape, depending on the nature of the sound field. The figure shows only one combination of ASW and LEV.

An alternative view is that ASW and LEV are an identical sense and that the difference between them is simply a matter of degree depending on the size. In other

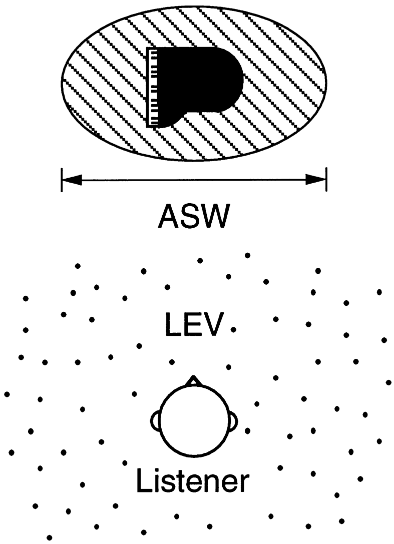

Fig. 1. Concepts of auditory source width (ASW) and listener envelopment (LEV).

words, spatial impression is a one-dimensional sense. For instance, a small degree of spatial impression could be termed as ASW and a large one as LEV. But the border between them is fuzzy.

Meanwhile, many pieces of research on physical measures related to spatial impression have been reported over the 20 years since Keet [7]. Among them, well-known measures are the lateral energy fraction and the degree of interaural cross-correlation. If spatial impression is a one-dimensional sense which can be evaluated by these measures, the results of the past experiments could yield a strange and interesting conclusion about the acoustical design of concert halls. Based on the character of the lateral energy fraction by Barron and Marshall [6], it can be concluded that the reflections with the same angle from the aural axis produce the same amount of ASW (though Barron and Marshall [5,6] use the term spatial impression as mentioned above, the present authors regard it as equivalent to ASW, from the definition of spatial impression used by them as mentioned above), when the sound pressure level of reflections are equal. Furthermore, Morimoto et al. [8,9] indicated that ASW produced by any sound field with the same degree of interaural cross-correlation measured without artificial ear simulators and A-weighting, so-called DICC [10], is identical, regardless of the number and the arriving direction of reflections. From these results, it can be concluded that it is possible to control spatial impression by reflections which arrive only from in front rather than behind the listener. In other words, reflections from behind the listener are not always necessary to produce spatial impression. However, there is evidence that sound from behind the listener is important. There must be some sense which needs reflections from behind the listener. Yamamoto [11] reported that one of the subjective measures for sound in rooms is correlated with front/back energy ratio that is the ratio of sound energy from in front to that behind the listener. But he did not make clear what its subjective significance was. The present authors suppose that it must be LEV.

The first report on the physical measure of LEV by Morimoto and Maekawa [4] in 1989 indicated that the degree of interaural cross-correlation of the late reflections relates to LEV. Furthermore, the recent papers by Bradley and Soulodre [2,3] in 1995 indicated the late lateral sound level LG best predicts LEV. From these last three pieces of work, it appears that the reflections from behind are not necessary in order to produce LEV. However, in each case the experiments were conducted with sound only arriving from in front of the listener.

The purposes of this paper are to make clear the role of reflections from behind the listener in the perception of spatial impression, to confirm that the listener can perceive LEV and ASW as two distinct senses of a sound image and to investigate whether or not the energy in the early part of the impulse response of a sound field contributes to LEV, and which is more effective for LEV, front/back energy ratio (FBR) in the early or late part of the impulse response of a sound field.

2. Methodology

The authors are of opinion that there are two approaches for studying on concert hall acoustics: one is to predict and evaluate physical and subjective characteristics of existing concert halls, and explains physical and subjective phenomena in them. From this standpoint a study will be made with parameters in a range actually observed in the existing concert halls. The other is to investigate physical and subjective phenomena, which could take place in realizable concert halls, regardless of whether they actually take place in existing concert halls or not. From this standpoint a study should sometimes include extreme cases, even if they are not observed in the existing concert halls.

Therefore, how to select conditions of experiments and calculations is often a subject of discussion in the field of concert hall acoustics. Some architectural acousticians cannot accept the results of experiments and calculations performed under conditions which cannot be observed in existing concert halls and criticize them as useless, because they sometimes confuse an existing concert hall with a realizable one: one should know that some architectural and acoustic conditions, which are different from those observed in all existing concert halls, can be realizable in concert halls.

The experiments in this paper are carried out from the standpoint of clarifying physical and subjective phenomena, which could take place in realizable concert halls. The main purpose is not to investigate LEV perceived in the existing concert halls, but to prove a hypothesis that reflections arriving from behind the listener contribute to the perception of LEV in spatial hearing. Therefore, a simple sound field is used and physical factors are changed extremely, whether they can be observed in the existing concert halls or not.

However, LEV in the existing concert halls can be inferred, if the relationships between LEV and the physical factors are clarified from the results of the experiments in this paper and if measured values of the physical factors in existing concert halls are presented.

3. Definition of front/back energy ratio

In this paper, front/back energy ratio (FBR) is introduced as a physical factor to investigate the effect of reflections arriving from behind the listener, as defined by Eq. (1):

$$\mathrm{FBR} = 10\log(E_\mathrm{f}/E_\mathrm{b}) \quad (\mathrm{dB}) \tag{1}$$

where E_f and E_b are energies of reflections arriving from in front and behind the listener, respectively. In this equation, the energy of the direct sound and reflections in the transverse plane, which is the plane that intersects both the horizontal and the median plane at right angles and contains the entrances of left and right ear canals, are excluded.

4. Experiment 1

It is well known that most of subjective evaluations in concert halls is related to the early part of the impulse response of a sound field. On the other hand, some authors have reported that the late part contributes to LEV as described in Section 5 [2–4,14,15]. However, there is no conclusive evidence of their findings. In this experiment, therefore, FBR in both of the early and late parts were identical to concentrate on the contribution of the reflections from behind the listener to LEV, setting a problem of which part contributes to LEV aside for the moment.

In this experiment, the effects of reflections from behind the listener on not only LEV but also ASW were investigated by changing FBR and the ratio of early to late sound energy, C_{80} (clarity). Therefore, this experiment is capable to determining whether the listener can perceive LEV and ASW independently [4] and for ASW if it is independent of the arrival direction or reflections from in front or behind listener [5,8,9].

4.1. Method

In this experiment, a violin solo performance of Saint-Saens' "Introduction et Rondo Capriccioso" (14 s long, bars 7–12) recorded in an anechoic chamber was used as a music motif. The parameters were FBR and C_{80}. DICC, that is the degree of interaural cross-correlation measured without artificial ear simulators and A-weighting [10,12], of the whole reflections (early reflections + reverberation), was kept constant.

Fig. 2 shows the arrangement of loudspeakers. Six loudspeakers each of which is installed in a cylindrical enclosure (diameter: 108 mm, length: 350 mm) were arranged at azimuth angles of 0° and ±45° from the median plane, that is, they were

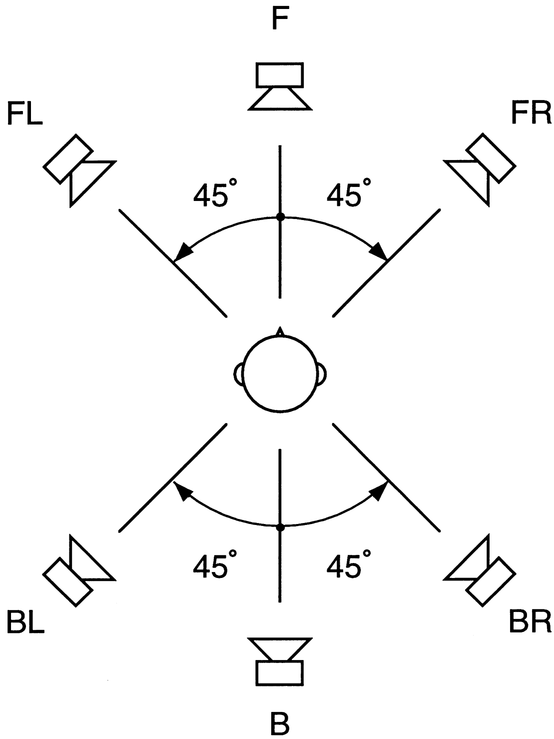

Fig. 2. Arrangement of loudspeakers in the experiments.

arranged symmetrically to the aural axis, in an anechoic chamber. The distance between the center of subject's head and the loudspeakers was 1.5 m. The frequency characteristics of all loudspeakers were flat within ±2 dB in the frequency range from 70 Hz to 9 kHz. Fig. 3 shows the impulse response of the stimulus. The sound field used as a stimulus consisted of a direct sound and four early discrete reflections and four reverberation signals. Their reverberation times were constant at 1.5 s and their frequency characteristics were flat. Reflection delays were 20, 38, 53 and 65 ms and reverberation delays were 80, 89, 97 and 104 ms.

The direct sound and the first early reflection were radiated from loudspeaker (F) and the second one was radiated either from loudspeaker (F) or (B). The third and fourth ones were radiated either from loudspeakers (FL) and (FR), respectively, or (BL) and (BR), respectively. The first and the second reverberation signals were radiated either from loudspeakers (FL) and (FR), respectively, or (BL) and (BR), respectively. When they were radiated from loudspeakers (FL) and (FR), the third and the fourth ones were radiated from loudspeakers (BL) and (BR), and when they were radiated from loudspeakers (BL) and (BR), the third and the fourth ones were radiated from (FL) and (FR). However, all reverberation signals were not radiated either only from loudspeakers (FL) and (FR) or only from loudspeakers (BL) and (BR).

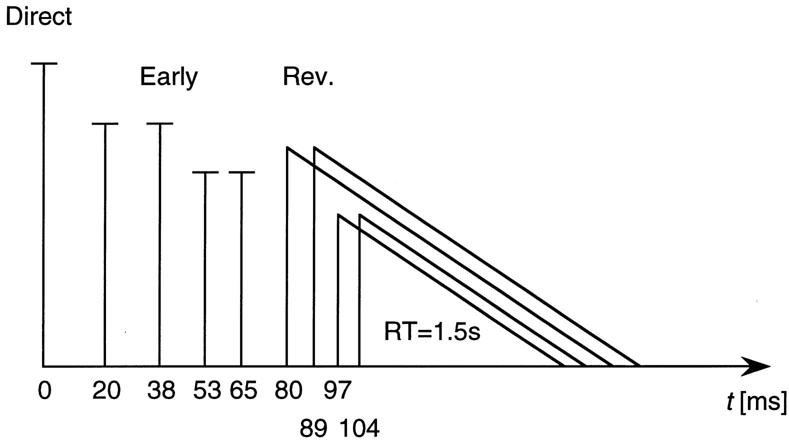

Fig. 3. Schematic diagram of impulse response of the stimulus used in the experiments.

The directions and the relative sound pressure levels of early reflections and reverberation signals depend on FBR and C_{80} of a stimulus. But the sound pressure levels of reflections from the left and the right were identical and reverberation signals from the left and the right were also identical, and they were radiated from loudspeakers arranged symmetrically to the aural axis so that DICC of the whole part (early reflections + reverberation signals) of a sound field as a stimulus would be constant.

FBR was set at −15, −7.5, 0, +7.5, and +15 dB. These values were obtained by measuring the energy from in front and behind separately with a one-point omnidirectional microphone. The FBR in the early reflection part and that in the reverberant part were the same. C_{80} was set at −11, −1, and +9 dB. The total number of stimuli was 15. DICC of the whole part of a sound field of all stimuli were constant at 0.65±0.05 measured by the KEMAR dummy head without an artificial ear simulator (B&K Type DB-100). The sound pressure levels of all stimuli were constant at 79.4±0.5 dBA slow, peak, measured at the left ear of the KEMAR dummy head without an artificial ear simulator.

Paired comparison tests were performed in the experiments. Two kinds of experiment were carried out relating to both LEV and ASW. In experiment 1a, FBR was changed keeping C_{80} constant in order to investigate the effects of FBR on LEV and ASW. In experiment 1b, C_{80} was changed keeping FBR constant in order to investigate the effects of C80 on LEV and ASW. However, in order to shorten the time necessary for the experiments, experiment 1a for ASW in which the FBR was changed was only conducted with a C_{80} of −1 dB. Experiment 1b for both LEV and ASW with C_{80} being varied was performed with FBR values of −15, 0, and +15 dB.

In experiment 1a, a paired comparison test was carried out separately for each C_{80}. For each C_{80} the test had 20 pairs including reversals. The interval between the two stimuli was 2 s. Each pair of stimuli was arranged in random order and separated by an interval of 5 s. In experiment 1b, a paired comparison test was carried out together for all FBR. The test had 18 pairs composed of six pairs including reversals for each FBR. As before, the interval between the two stimuli was 2 s. Each pair of stimuli was arranged in random order and separated by an interval of 5 s in the same way as experiment 1a.

In both experiments, LEV and ASW were tested separately. Each subject was tested individually and 10 times for each pair, while seated, with head fixed. The task of the subject was to judge which LEV is greater or which ASW is wider. Before the experiments, the concepts of LEV and ASW were explained to the subject by using Fig. 1. Five male students with normal hearing sensitivity acted as subjects for the experiments. They had sufficient experience as subjects in this kind of experiment.

4.2. Results and discussion

In both experiments, 50 responses to each pair (5 subjects by 10 times) were obtained in total. The psychological scales of LEV and ASW were obtained using the Thurstone Case V model [13]. The following must be considered in interpreting the psychological scales obtained using this model: the psychological scales obtained from the experiments performed separately are not comparable. The difference of 0.68 on any psychological scale means that the probability of discrimination of difference between two stimuli is 75%. Therefore, it is generally considered that the difference of 0.68 on the psychological scale corresponds to the just noticeable difference (jnd).

Fig. 4 shows the psychological scale of LEV in experiment 1a, that is, LEV vs. FBR for each C_{80}. For each C_{80} value, LEV increases as FBR decreases. The difference between the maximum and the minimum LEV exceeds 0.68 for each C_{80} value. This means that FBR significantly affects LEV which the listener perceives. Namely, LEV increases as the sound energy from behind the listener increases. Furthermore, this tendency seems to be greater for the lower C_{80}. This suggests that the perception of LEV is related to the law of the first wave front. As C_{80} decreases, the energy of the reverberation increases and as a result, the energy of the component of reflection beyond the upper limit of the law which can contribute to the perception of LEV increases. In other words, FBR of the late reflections (reverberation) may be more effective for LEV than that of the early reflections.

Fig. 5 shows the psychological scale of LEV in experiment 1b, that is, LEV vs. C_{80} for each FBR. LEV is maximum at C_{80} of −1 dB for any FBR. But the difference between the maximum and the minimum LEV does not exceed 0.68 for FBR of 0 and +15 dB, while the difference for FBR of −15 dB exceeds 0.68. From these results, it cannot be concluded whether or not the effect of C_{80} on LEV is significant. On the other hand, Bradley and Soulodre [3] concluded that C_{80} significantly affected LEV. According to their experimental results, LEV increases at C_{80} decreases from 7 to 1 dB. Furthermore, the results of ANOVA show that C_{80} significantly affects perceived LEV.

It seems that the following reasons caused the difference between the two conclusions. The first reason is that the data analyzing method is different. In their experiments, paired comparison test were performed in which subjects rated the magnitude of the difference of LEV between each pair of sound fields with different C_{80} from 1 to 7 dB. Subjects rated the magnitude of the difference in LEV using a five-point response scale. A score of 1 indicated that the two sound fields had the same LEV. A score of 5 indicated the largest expected difference in LEV. An analysis of variance test of the results showed that there was a highly significant main effect of C_{80}, but this does not necessarily mean that the difference is psychologically significant. On the other hand, in this paper, the significance of the difference in LEV is discussed on the basis of jnd of LEV. Namely, the present authors investigate whether or not C_{80} is psychologically significant. The second reason is that the range of the change of C_{80} is different. C_{80} varied from 1 to 7 dB in the experiments by Bradley and Soulodre [3] while it varied from −11 to 9 dB in the present experiments. However, the results of the present experiments also show that LEV increases as C_{80} decreases in the limited range from 9 to −1 dB, and that the difference in LEV exceeds 0.68 for FBR of −15 dB. By the way, Fig. 5 shows the highest LEV with a C_{80} of −1 dB,

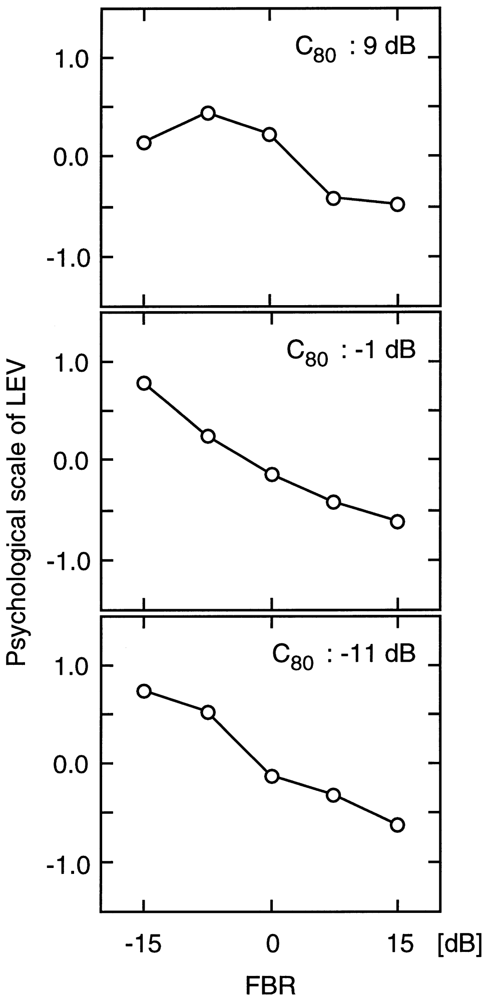

Fig. 4. Psychological scale of LEV as a function of FBR for each C_{80}.

which is not an obvious result. However, any reasonable explanation for this tendency has not yet been obtained, and a further study will be needed to gain more insights.

Fig. 6 shows the psychological scale of ASW in experiment 1a. Experiment 1a for ASW was performed under the condition in which FBR was changed at only C_{80} of −1 dB as mentioned above. There is no noticeable difference more than 0.68 between any FBR. This result coincides with the previous observations [8,9] that ASW perceived in any sound field with the same DICC are identical, regardless of the arriving direction of reflections. Comparing the middle graph of Fig. 4 with Fig. 6, it is reconfirmed that ASW is independent of whether the reflections arrive from in front or behind the listener and that LEV and ASW can be perceived independently since LEV changes but ASW is constant when FBR changes.

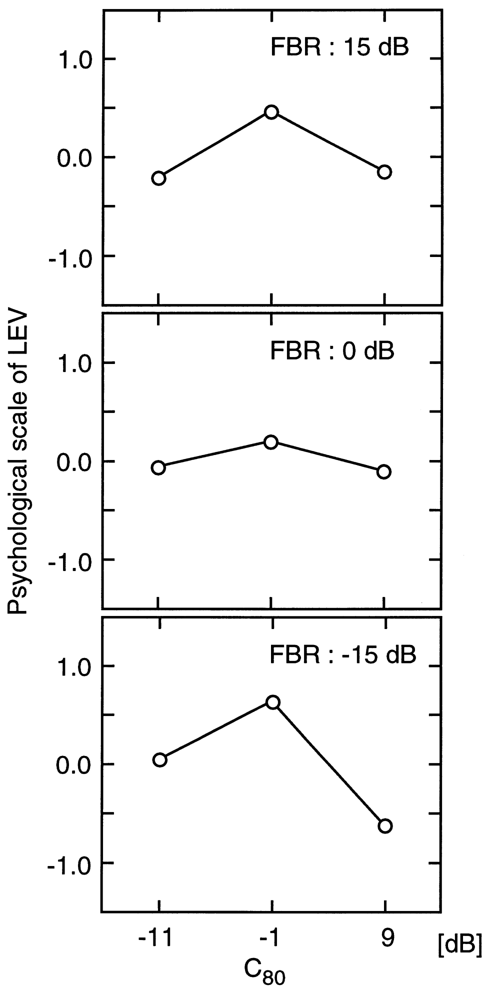

Fig. 5. Psychological scale of LEV as a function of C_{80} for each FBR.

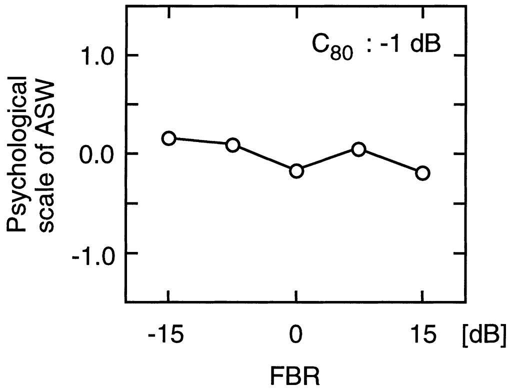

Fig. 6. Psychological scale of ASW as a function of FBR for C_{80} of -1 dB.

Fig. 7 shows the psychological scale of ASW in experiment 1b, that is, ASW vs. C_{80} for each FBR. There is no noticeable difference more than 0.68 between any C_{80} for any FBR, neither. This result supports the result of the previous observation [12] that the whole part of the impulse response of a sound field contributes to the perception of ASW. Because, if it were a part of the impulse response that contributes to the perceived ASW, C_{80} would affect the perceived ASW.

The results of experiment 1 are summarized as follows: it can be concluded that the role of reflections arriving from behind the listener is to increase LEV in spatial impression. In addition, it can be reconfirmed that the listener can perceive LEV and ASW as two distinct senses of a sound image, and that ASW is independent of whether the reflections arrive from in front or behind the listener.

5. Experiment 2

The definitions of LEV both by Beranek [14] and by ISO [15] mean that the late part of the impulse response of a sound field contributes to LEV. Morimoto and Maekawa [4] also demonstrated that the degree of interaural cross-correlation of the late reflections relates to LEV. Furthermore, Bradley and Soulodre [2,3] proposed the relative level of the late lateral sound energy as a physical measure of LEV. However, at present, there exists no psychoacoustic evidence that the early part does not contribute to the perception of LEV at all. Bradley and Soulodre suggested the relation between the perception of LEV and Haas effect, [16], that is, the law of the first wave front. Meanwhile, Morimoto and Iida [1] showed that only the energy of the components of reflections under the upper limit of the law of the first wave front contributes to ASW, when the reflections do not satisfy the law. This fact hints that the components of reflections beyond the upper limit of the law contributes to LEV. If the perception of LEV is in relation to the law, any reflection which exceeds the upper limit of the law must contribute to LEV, regardless of its delay time relative to the direct sound. The results on LEV obtained in experiment 1 suggest that FBR in the late part (reverberation) is more effective for LEV than that in the early part, as mentioned above. However, it could not be concluded which is more effective for LEV, FBR in the early part of the late part, because FBR in both parts were identical in the experiment.

The purpose of experiment 2 is to make clear whether or not the energy in the early part of the impulse response of a sound field contributes to LEV, and which is more effective for LEV, FBR in the early or late part of the impulse response of a sound field. In the experiment, FBR in the early or late parts were changed independently. The boundary between the early and the late was 80 ms relative to the direct sound.

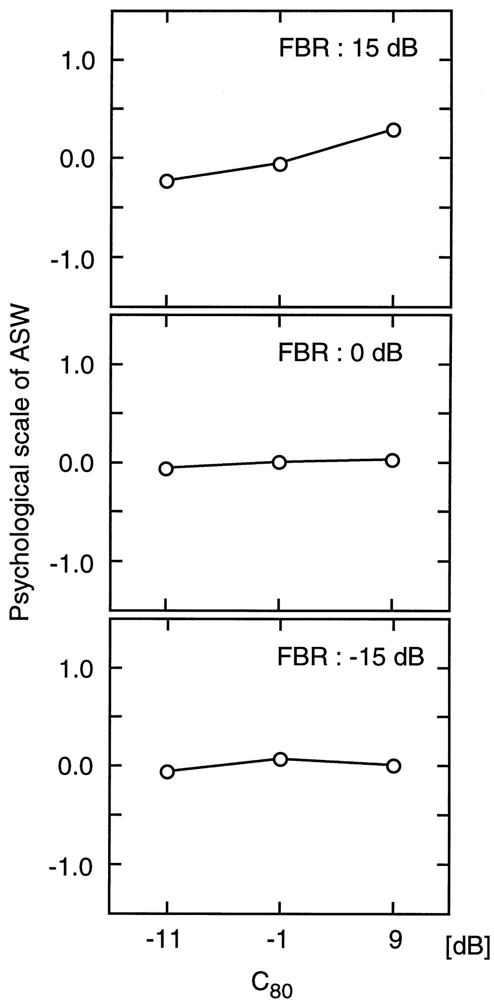

Fig. 7. Psychological scale of ASW as a function of C_{80} for each FBR.

5.1. Method

The major part of the method in this experiment was the same as that in experiment 1. The music motif, the loudspeakers, the loudspeaker arrangement, the frequency characteristics of loudspeaker, and the impulse response of stimulus which were used in this experiment were the same as those used in experiment 1. Furthermore, each loudspeaker, which provided each reflection and each reverberation signal, was the same as that in experiment 1. The directions and the relative sound pressure levels of early reflections and reverberation signals depend on FBR in each the early and the late parts.

FBR in the early part was set at −13.7, +0.1 and +14.5 dB and FBR in the late part was set at −15.0, +0.4 and +14.4 dB. FBR in the early part and that in the late part were changed independently. The total number of stimuli was nine. C_{80} ranged from +0.2 to +1.1 dB. As a result, FBR in the whole part (early part + late part) of the sound field as a stimulus ranged from −14.7 to +14.5 dB. Furthermore, DICC of the whole part ranged from 0.26 to 0.45, measure by the KEMAR dummy head without an artificial ear simulator (B&K Type DB-100), because FBR in the early part and the late part were not always the same. But it can be considered to be constant on the basis of jnd [10]. The sound pressure levels of all stimuli were constant at 80.0 dBA slow, peak, measured at the left ear of the KEMAR dummy head without an artificial ear simulator.

Paired comparison tests were performed in the experiments. The test had 36 pairs. The interval between the two stimuli was 2 s. Each pair of stimuli was arranged in random order and separated by an interval of 7 s. Each subject was tested individually and 10 times for each pair, while seated, with head fixed. The task of the subject was to judge which LEV is greater. Before the experiments, the concept of LEV was explained to the subject by using Fig. 1. Five male students with normal hearing sensitivity acted as subjects for the experiments and they have sufficient experience as subjects in this kind of experiment, but they were different from the subjects in experiment 1.

5.2. Results and discussion

In the experiment, 50 responses to each pair (five subjects by 10 times) were obtained in total. The psychological scales of LEV were obtained using the Thurstone Case V model [13]. As mentioned in Section 4.2, it is generally considered that the difference of 0.68 on the psychological scale corresponds to jnd.

Fig. 8 shows the psychological scale of LEV as a function of FBR in the early part and as a parameter of FBR in the late part. FBR of the whole part of a sound field which makes the listener perceive the maximum LEV is −14.7 dB, and in contrast, FBR of the whole part of a sound field which makes the listener perceive the minimum LEV is +14.5 dB. The difference between the maximum and the minimum LEV is 1.75. This difference is almost equal to the difference between LEV for FBR of −15 and +15 dB in experiment 1 as shown in Fig. 4, though the subjects in the first and the second experiments were different. Therefore, LEV obtained in both experiments can be regarded as being reasonable.

The results show that FBR in the early part affects LEV as well as that in the late part. There is an overall tendency that the decreasing of FBR in the early part increases LEV. Furthermore the difference between the maximum and the minimum LEV exceeds 0.68 for FBR in the late part of −13.7 and +0.1 dB. From the results, it can be concluded that FBR in the early part also affects LEV. In other words, the early part can also contribute to the perception of LEV. Meanwhile, the decreasing of FBR in the late part increases LEV for any FBR in the early part. Furthermore, the difference between the maximum and the minimum LEV clearly exceeds 0.68 for any FBR in the early part. From the results, it can be concluded that FBR in the late part effects LEV.

The multiple regression analysis was used to investigate which is more effective for LEV, FBR in the early or late part. The multiple regression equation is given in Eq. (2). The multiple correlation coefficient is 0.956.

$$\text{LEV} = -0.018\ (\text{early}) - 0.041\ (\text{late}) + 0.901 \tag{2}$$

This equation indicates that the contribution of the late part to LEV is about twice as much as that of the early part. In this experiment, C_{80} was ranged from +0.2 to +1.1 dB. Therefore, it might be considered that this result was caused by the reason that the energy in the early part was less than that in the late part, but it is unrealistic, because a change in LEV as a function of FBR of whole part decreases at C_{80} increases; that is, the energy of the early part increases, as shown in Fig. 4. Furthermore, following the law of the first wave front, it is easy to speculate that the energy in the late part which exceeds the upper limit of the law by more than does the early part in the situation when the levels of the reflections in both parts are identical. In conclusion, one can say that the FBR of the late part is more effective for LEV than is the early part of the impulse response.

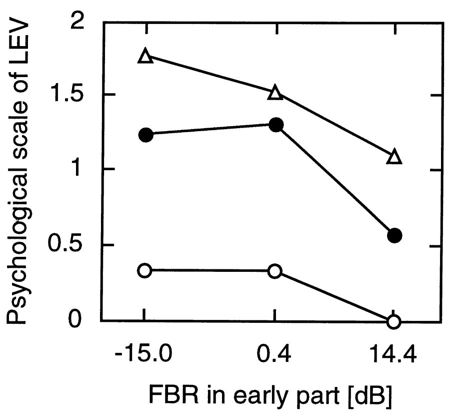

Fig. 8. Psychological scale of LEV as a function of FBR in the early part and as a parameter of FBR in the late part. Triangle, closed circle and open circle indicate LEV for FBR in the late part of −13.7, +0.1, and +14.5 dB, respectively.

6. Conclusions

In experiment 1, the subjective experiments on LEV and ASW were performed by changing the FBR and C_{80} while keeping the degree of interaural cross-correlation of the whole part of the impulse response of the sound field constant. The results show that FBR significantly affects LEV. LEV increases with a decrease of FBR, that is when the portion of reflected energy arriving from behind the listener increases. On the other hand, ASW is independent of whether the reflections arrive from in front or behind the listener so that FBR does not affect ASW. From these results, it can be concluded that the listener can perceive LEV and ASW as two distinct senses of a sound image and that the role of reflections arriving from behind the listener is to increase LEV in spatial impression. It cannot be definitely concluded whether C_{80} affects LEV or not.

In experiment 2, subjective experiments on LEV were performed by changing the FBR in the early and the late parts of the impulse response of a sound field independently. The results show that the FBR in the early part also contributes to the perception of LEV but that the FBR of the late part is more effective for LEV than that of the early part.

In both experiments, major changes were made to the FBR in order to determine the effects of FBR more clearly. The results indicate that a change of about 15 dB in FBR causes a noticeable change in LEV. Note that, even if a difference in FBR between seats within concert halls or between different halls is less than 15 dB, it does not mean that FBR is not useful for subjective evaluation of existing concert halls, but that there is no noticeable difference between LEV perceived at different existing seats or in different existing concert halls. It is clear that in concert halls where the rear wall is highly absorbent the FBR will be large and the perceived LEV will be small. In this condition more reflections from behind the listener will play a role in creating LEV.

In addition, one should not jump to the conclusion that reflections arriving only from exactly behind the listener can make the listener perceive LEV. A preliminary experiment with direct sound and reflections only from directly behind the listener showed that a sense of envelopment is not produced in this situation, even with significant reflection energy. In this condition the listener perceives a somewhat broad sound image in front of him and a sharp sound image exactly behind him, but no feeling of envelopment. This suggests that the spatial distribution of reflections plays an important role in the perception of LEV as well as FBR.

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