The relation between spatial impression and the law of the first wavefront

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Abstract

In the field of room acoustics, it is popular belief that the early and late reflections contribute to auditory source width (ASW) and listener envelopment (LEV), respectively. However, some papers have demonstrated results not necessarily in agreement with the belief. In this paper, a hypothesis is proposed to clarify the essentials of ASW and LEV from point of view of the auditory phenomenon. The hypothesis is that the components of reflections under and beyond the upper limit of validity for the law of the first wavefront contribute to ASW and LEV, respectively. Two experiments were performed to evaluate the hypothesis. In the first experiment, the results showed directly that the components of reflections under the upper limit of validity for the law contribute to ASW. In the second experiment, four kinds of threshold were measured to evaluate the relation between the effect and LEV: image-splitting which corresponds to the upper limit of validity for the law, LEV, reverberation perception, and reverberation disturbance. The results showed that the threshold of image-splitting coincides with the that of LEV. This suggests that the components of reflections beyond the upper limit of validity for the law contribute to LEV. In conclusion, it seems that the results of experiments shown in this paper favor the hypothesis.

1. Introduction

In 1989, Morimoto and Maekawa demonstrated that spatial impression comprises at least two components and that a listener can discriminate between them [1]. One is auditory source width (ASW) which is defined as the width of a sound image fused temporally and spatially with direct sound image, and the other is listener envelopment (LEV) which is defined as the degree of fullness of sound images around the listener, excluding a sound image composing ASW [1,2], although the terminology used to describe those aspects of spatial impression has been confused for some time. Now, these concepts are well established including the definitions of ASW and LEV [3,4].

Many pieces of research on physical measures related to spatial impression have been reported over the 20 years since Keet [5] in the field of room acoustics. Among them, well-known measures are the lateral energy fraction [6] and the degree of interaural cross-correlation [5,7,8]. Furthermore, it was recently demonstrated that some other factors, such as late lateral sound level [3], front / back energy ratio [2,9], directional energy ratio [10] and spatially balanced Ts [11], are related to the perception of LEV.

Generally speaking, these measures and factors depend on reflections which are divided into an early and late part. The relevant time interval for early reflections with music is 80 ms while that for speech is 50 ms. Recently, Soulodre et al. [12] have demonstrated that the time is frequency dependent. In the former way of thought [13,14], the early and late reflections contribute to ASW and LEV, respectively. However, Morimoto and Maekawa [1] demonstrated that the late reflections also contribute to ASW. The results of other experiments by Morimoto et al. [9] and Furuya et al. [15] indicated that the early reflections also contribute to LEV. Furthermore, Bradley and Soulodre [4] demonstrated that the early-to-late sound index, C80 can affect LEV, whereas Morimoto et al. [9] showed that C80 may have no such effect. Thus, the division of reflections into the early and late parts does not always give a reasonable explanation of such an auditory perception, though the division is certainly convenient from a practical point of view.

Meanwhile, Bradley et al. [16] examined how judgments of ASW and LEV influence each other. That is, whether adding late lateral sound energy affects the perception of ASW in real concert halls and whether adding early lateral sound energy affects the perception of LEV in real concert halls. As a result, they indicated that early-arriving sound is a more effective masker of late sound for LEV than is late-arriving sound for ASW. To explain these phenomena and possible practical questions in the future, it is important to make clear the essentials of ASW and LEV, that is, the necessary conditions for the perception of ASW and LEV from the point of view of the auditory phenomena.

An essential point is that an auditory temporal window does not have a rectangular shape, but it has a slope at each end. Therefore, the conventional rectangular division of reflections into an early and late part in time is overly simplistic. As suggested by the definitions of ASW and LEV mentioned before, the perception of them relates strongly to the law of the first wavefront [17]. Namely, as Bradley and Soulodre describe in their paper [4], sound arriving shortly after the direct sound is integrated or temporally and spatially fused with the direct sound. Thus, increasing levels of early lateral reflections increase the apparent level of the direct sound and cause a slight ambiguity in its perceived location. These two effects contribute to the resulting increase in ASW. Later arriving sound is not integrated or temporally and spatially fused with the direct sound, and leads to more spatially distributed effects that appear to envelop the listener. This description well explains the relation between the perception of spatial impression and the law. However, it is insufficient for a deep understanding of the relation, because it is qualitative but not quantitative.

Here, to facilitate understanding of the relation, let us suppose a simple sound field consisted of a direct sound and a single lateral reflection of constant level. According to the law, when the delay time of the reflection does not exceed a critical value, which depends on the kind of source signal, only one sound image is perceived in the direction of the direct sound. Then, ASW is perceived, but LEV is not as explained above. That is, the reflection contributes only to ASW. On the other hand, when the delay time exceeds the critical value, two sound images are perceived separately in the directions of the direct sound and the reflection [18]. This phenomenon is called “image-splitting.” Then, LEV is perceived as explained above. Furthermore, only LEV is perceived, based on the conventional physical measures which divide reflections into an early and late part. However, some questions arise from this case. Should not ASW also be perceived simultaneously? If ASW is also perceived, how much does the reflection contribute to create each of ASW and LEV?

Barron [19] investigated the relation between delay time of reflection and ASW (The term “spatial impression” was used in his paper.) using a sound field consisting of a direct sound and two reflections and demonstrated that ASW did not change even for a long delay time of reflections in which echo disturbance occurred. This means that even when reflections are not fused with a direct sound, they still contribute to ASW as much as when reflections are fused with a direct sound. Furthermore, they create LEV simultaneously, according to the definitions of ASW and LEV and the description by Bradley and Soulodre [4] mentioned before.

On the other hand, the previous paper [20] demonstrated that ASW of a sound image perceived in the direction of the direct sound, when the delay time of the reflection exceeds the critical value and two sound images are perceived separately, is narrower than that when the delay time does not, but wider than that for only a direct sound without a reflection. This suggests that even if the delay time of the reflection exceeds the critical value, the reflection partially contributes to the perception of ASW as a lateral reflection. Furthermore, the previous paper demonstrated quantitatively that a part of the reflection under the upper limit of validity for the law of the first wavefront contribute to create ASW when the reflection exceeds the upper limit of validity for the law.

Meanwhile, how much do the reflections not fused with a direct sound contribute to create LEV? Based on the conventional physical measures which divide reflections into an early and late part, it is assumed that whole energy of those reflections fully contribute to create LEV. However, this is not yet proved. Thus, a quantitative explanation about the relation between the law and the perception of ASW and LEV is required.

The present authors believe that the listener perceives not only one sound image fused temporally and spatially with the direct sound image based on the law, but also the other ones caused by reflections not affected by the law, in enclosed spaces. 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.

On the basis of these facts, the authors make the following quantitative hypothesis on the relation between spatial impression and the law of the first wavefront. Figure 1 is a schematic diagram to explain the hypothesis on the relation between them. Suppose that a sound field consists of a direct sound and several reflections. A dot-dash line indicates the upper limit of validity for the law (as a matter of fact, the upper limit is affected by reflections before and after and exhibits a complex behavior). Solid and dotted lines of reflections indicate the components of reflections under and beyond the upper limit, respectively. The hypothesis is that the components of reflections under and beyond the upper limit of validity for the law contribute to ASW and LEV, respectively.

The previous paper [20] has already established the hypothesis on the relation of ASW and the law as mentioned before. In this paper, the relation between LEV and the law is investigated. Specifically, this is investigated whether or not a listener begins to perceive LEV while he begins to perceive image-splitting, the threshold of which corresponds to the upper limit, since it is critical to support the hypothesis that the components of reflections beyond the upper limit of validity for the law of the first wavefront contribute to LEV.

2. The relation between ASW and the law of the first wavefront

Although evidence for the relation between ASW and the law of the first wavefront has already been published by Morimoto and Iida [20], it is repeated here for readers' convenience and to facilitate understanding of the other proposed relation, that is, the relation between LEV and the law. They performed two experiments. In the first experiment, ASW created by a reflection which exceeds the upper limit of validity for the law was compared with ASW created by a reflection which does not exceed the limit. In the second experiment, the quantitative relation between ASW and the law was clarified.

2.1. Experiment 1: Paired comparison of ASW produced by a reflection beyond and under the upper limit of validity for the law

2.1.1. Experimental method

The music motif used in the experiment was a 7 s section from the beginning of Partita a-moll für flute allein BWV 1013 by J. S. Bach. The motif was performed with an electronic music synthesizer. Morimoto and Maekawa [8] demonstrated that low frequency components contribute to create ASW much more than high frequency. However, it does not mean that high frequency components never contribute to create ASW. In fact, the subjects could perceive ASW in this experiment. The important point in this experiment is to produce the experimental condition that it is easy for the subjects to judge whether image-splitting occurs. Since high frequency components were easier than low ones for the subject to judge it according to the result of the preliminary listening tests, the music motif composed of high frequency components was used in the experiment.

Figure 2 shows the loudspeaker arrangement in the experiment. The direct sound was radiated from the front of a subject and the reflection was radiated from the azimuth angle of 135° on the left side so that the subject could discriminate easily between the sound image perceived in the direction of the direct sound and that in the direction of the reflection when image-splitting occurred.

Six kinds of stimuli were used in the experiment according to the results of the preliminary experiment. Figure 3 shows their impulse responses. The stimuli (a), (b), (c) and (d) consist of a direct sound and a single reflection. For stimuli (a) and (b), the reflection does not exceed at all the upper limit of validity for the law of the first wavefront. Namely, all of the subjects perceive only one sound image in the direction of the direct sound. On the other hand, for stimuli (c) and (d), the reflection absolutely exceed the upper limit. Namely, all of the subjects perceive one-by-one sound image separately in each direction of the direct sound and the reflection. The stimuli (e) and (f) consist of only a direct sound. The sound pressure levels of the direct sound and the reflection for stimuli except (f) were equal to each other. The level of the direct sound for stimulus (f) was higher than those of the other stimuli by 3 dB. The sound pressure level of 0 dB in Fig. 3 was 69dBA, slow, peak, measured at the position corresponding to the center of the subject's head.

Paired comparison tests were performed in the anechoic chamber. The test had 30 pairs including reversals. The interval between the two stimuli was 1 s. Each pair of stimuli was arranged in random order and separated by an interval of 5 s. Each subject was tested individually, while seated, with head fixed. The experiment was carried out four times for each subject. The task of the subject was to judge which ASW is wider. When the subject perceived two sound images separately, he was required to judge the width of the sound image perceived in the direction of the direct sound, disregarding that in the direction of the reflection. Subjects were five male students, 22-25 years of age, with normal hearing sensitivity.

2.1.2. Experimental results and discussion

The psychological scales of ASW were obtained using the Thurstone Case V model [21]. However, the scale of ASW for stimulus (e) could not be obtained because all subjects perceived it narrower than ASW for all other stimuli. The following must be considered in interpreting the psychological scales obtained using this model. The difference of 0.68 on the 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 scale corresponds to the just noticeable difference.

Figure 4 shows the psychological scale of ASW for stimuli except stimulus (e). The differences between ASW for stimuli (a) and (b) and between ASW for stimuli (c) and (d) are 0.16 and 0.10, respectively. Both of them are not noticeable differences. Comparing ASW for stimuli (a) and (b), when the reflection does not exceed the upper limit of validity for the law of the first wavefront, and ASW for stimuli (c) and (d), when the reflection exceeds the limit, the average difference is 1.59. This is a noticeable difference, because the difference of 1.59 means that the probability of discrimination of difference between them is 94.4%. As a result, it can be considered that ASW for the former stimuli are wider than ASW for the latter stimuli. In other words, ASW perceived when the subject perceives one sound image is clearly wider than ASW perceived when the subject perceives two sound images separately.

This result disagrees with Barron's result that the reflection of the same sound pressure level produces almost the same ASW, regardless of its delay time, even if it causes echo disturbance (see Fig. 5 in Ref. [19]). The disagreement could be caused by the direction of the reflection in the experiment. As mentioned above, in our experiment, the reflection was radiated obliquely from behind the subject (the azimuth angle of 135° on the left side) so that the subject could discriminate easily between the sound image perceived in the direction of the direct sound and that in the direction of the reflection when image-splitting occurred for long delays. Namely, the subject judged ASW of only the sound image perceived in the direction of the direct sound, separated from the sound image in the direction of the reflection. On the other hand, the reflection was radiated from the azimuth angle of 40° in Barron's experiment. As he mentioned in his paper [19], the subject had to ignore the disturbing qualities of the reflection for long delays in his experiment. Namely, a possible cause is that the subject could not judge ASW of only the sound image perceived in the direction of the direct sound, but judged ASW of the sound image of the reflection temporally separated from the direct sound together.

Furthermore, comparing ASW for stimuli (c) and (d), when the reflection exceeds the upper limit of validity for the law, and ASW for stimulus (f), when only the direct sound is radiated, the average difference is 0.92. This is a noticeable difference. Namely, it can be considered that ASW for the former stimuli are wider than the latter stimulus. This means that the reflection contributes to produce ASW as a lateral reflection, even if the reflection exceeds the upper limit, that is, image-splitting occurs. However, a whole part of the reflection does not contributes to produce ASW, but a part of the reflection does, because ASW for stimuli (c) and (d) are narrower than stimuli (a) and (b), as mentioned above.

2.2. Experiment 2: ASW produced by the reflection beyond the upper limit of validity for the law

Two experiments were performed in an anechoic chamber to clarify the relation between ASW and the law. In the experiment 2a, the upper limit of validity for the law of the first wavefront was obtained and in the experiment 2b, ASW produced by the reflection which exceeds the upper limit was measured. The music motif and the arrangement of loudspeakers used in both experiments were the same as those in experiment 1. Subjects were three male students (A, B and C), 22-25 years of age, with normal hearing sensitivity, but they were different from the subjects in experiment 1.

2.2.1. Experiment 2a: Measurement of upper limit of validity for the law

In the experiment 2a, the reflection level, at which image-splitting begins to occur, was measured. The level corresponds to the upper limit of validity for the law. Figure 5 shows the impulse response of stimulus. The time delay of the reflection was constant at 80 ms. The experiment was performed using the method of constant stimuli, keeping the time delay of a single reflection constant, and changing the sound pressure level of the reflection. The sound pressure level of the direct sound was constant at 69 dBA (slow, peak), measured at the position corresponding to the center of a subject’s head. The relative level of the reflection to the direct sound, ΔLsp was changed in eleven steps of 1 dB from –5 to –15 dB.

Each stimulus was presented to each subject 50 times in random order. The mapping method was adopted to avoid the subject being too sensitive to the reflection. Namely, the subject's task was to mark down the direction and the range of the sound image on a circle on the recording sheet for each stimulus. When the subject perceived multiple sound images, he was requested to mark down all those directions and areas on the same circle.

In analyzing data, it was judged that image-splitting occurred when two ranges of sound images were marked separately on a circle on the recording sheet. The data analysis of the experiment was done separately for each subject by using the normal-interpolation process as described illustratively in detail at Sec. 3.2. As a result, measured ΔLsp was –7.0, –9.3 and –10.3 dB for the subjects A, B and C, respectively.

2.2.2. Experiment 2b: Measurement of ASW produced by the reflection beyond the upper limit of validity for the law

Figure 6 shows the impulse responses of the stimuli used in experiment 2b. Figure 6(a) is the impulse response of the stimulus (a), the reflection in which exceeds the upper limit of validity for the law. The time delay and the relative level of the reflection to the direct sound were fixed at 80 ms and 0 dB, respectively. Then, image-splitting occurred absolutely and the subject perceived two sound images, according to the results of the preparatory experiment. Figure 6(b) is the impulse response of the stimulus (b), the reflection in which does not exceed the upper limit of validity for the law. The time delay of the reflection was fixed at 20 ms. Meanwhile, the relative sound pressure level of the reflection to the direct sound, ΔLasw, was changed in eleven steps of 1dB from –5 to –15 dB. According to the results of the preparatory experiment, image-splitting did not occur at all and the subject perceived one sound image in the direction of the direct sound, even if the relative sound pressure level of the reflections to the direct sound was 0 dB. The binaural summation of loudness [22] of the total sound pressure levels of the direct sound and the reflection of all stimuli were constant at 71.4 dBA (slow, peak).

The purpose of this experiment was to obtain the sound pressure level of the reflection, ΔLasw, in the stimulus (b), when ASW for the stimuli (a) and (b) were the same. The experiment was performed by using the method of constant stimuli, comparing ASW for stimuli (a) and (b). A pair of the stimulus (a) and one of the eleven stimuli (b) was delivered. The subject was requested to answer which ASW of the sound image perceived in the direction of the direct sound was wider. Note that when the subject perceived two sound images separately, the subject judged ASW of the sound image perceived in the direction of the direct sound, separated from the sound image in the direction of the reflection. Each pair was presented to each subject fifty times in random order.

The data analysis of the experiment was done separately for each subject by using the normal-interpolation process as done in experiment 2a. As a result, measured ΔLasw was –7.0, –10.0 and –9.7 dB for the subject A, B and C, respectively. Every value is lower than the reflection level (= 0dB) for the stimulus (a). This means that ASW for the stimulus (a) is narrower than that for the stimulus (b) if the reflection level is identical. This result coincides with the result of experiment 1. Furthermore, it can be considered that the part of the reflection under ΔLasw contributed to produce ASW when the reflection exceeds the upper limit of validity for the law of the first wavefront.

2.2.3. Comparison of results of experiment 2a and 2b

As a result of experiment 2a, the relative level, ΔLsp, of the reflection which began to cause image-splitting was obtained. In other words, the upper limit of validity for the law of the first wavefront was obtained. Meanwhile as a result of experiment 2b, the relative level, ΔLasw, of the reflection not exceeding the upper limit, which produced the same ASW as the reflection exceeding the limit produced, was obtained. Table 1 compares ΔLsp and ΔLasw for each subject. Surprisingly, the two values for subject A are identical. The maximum difference between ΔLsp and ΔLasw is 0.7 dB for subject B. From these results, it can be considered that ΔLsp is equal to ΔLasw.

In conclusion, these results support the hypothesis that the components of reflections under the upper limit of validity for the law of the first wavefront contribute to ASW.

3. The relation between LEV and the law of the first wavefront

The purpose of the third experiment is to evaluate the hypothesis that the components of reflections beyond the upper limit of validity for the law of the first wavefront contribute to LEV. To achieve the purpose, four thresholds were measured by the listening tests: image-splitting which corresponds to the upper limit of validity for the law of the first wavefront as mentioned before, LEV, reverberation perception and reverberation disturbance. The reason why thresholds of reverberation perception and reverberation disturbance were measured in addition to thresholds of image-splitting and LEV is as follows: As is well known, image-splitting and reverberation perception are the same phenomenon in respect that sound images of a direct sound and a reverberation signal are perceived separately. However, they are contrary phenomena and their thresholds are quite different [23]. In the case of image-splitting, a subject listens to a direct sound, that is, a target is a direct sound and a reverberation signal works as an interfering sound. On the contrary, in the case of reverberation perception, a subject listens to a reverberation signal, that is, a target is a reverberation signal and a direct sound works as an interfering sound. Therefore, it is necessary to examine whether or not, the subjects judged the image-splitting correctly. As for reverberation disturbance, if there is little difference between reverberation disturbance and LEV, whenever the listeners perceive LEV, they are disturbed by reverberation. Therefore it is important to know how much is the difference between their thresholds.

3.1. Method

In all experiments for four kinds of thresholds, the source signal, the impulse response and the arrangement of loudspeakers of a test sound field used as a stimulus were identical.

The music motif used for the experiments was a 7 s section of the 1st movement of Mozart's Divertimento in F major, K. 138 (125c) recorded in an anechoic chamber.

Figure 7(a) shows the arrangement of loudspeakers. Three cylindrical loudspeakers (diameter 108 mm, length 350 mm) were arranged on the horizontal plane, including the subject's aural axis, in an anechoic chamber. The first loudspeaker was 1.5 m in front of the subject. The other two loudspeakers were placed at horizontal angles of ±135° from the median plane, also at a distance of 1.5 m. The frequency characteristics of all loudspeakers were equalized within ±5 dB in the frequency range from 100 Hz to 10 kHz by a frequency equalizer (Technics SH-8065).

Figure 7(b) shows the impulse response of the sound field used for the experiment. The sound field consisted of a direct sound and two coherent reverberation signals. Their reverberation times were constant at 2.0 s and their frequency characteristics were flat. Reverberation delays were 80 and 81 ms. The sound pressure level of the direct sound was kept constant at 70 dBA, slow, peak measured at the position corresponding to the center of the subject’s head. The loudspeaker at 0° radiated a direct sound and the other loudspeakers at ±135° radiated reverberation signals. The reason why the reverberation signals were radiated obliquely from the behind the subject was mentioned before.

Each threshold is the function which has three arguments, that is, the delay time, the relative sound pressure level and the direction of reverberation signals. All thresholds were obtained using the method of constant stimuli, keeping the delay time and the direction constant, and changing the relative sound pressure level. The relative sound pressure level of the initial amplitude of each reverberation signal to the direct sound, ΔL, was changed in random order. From the results of the preparatory experiment, ΔL were changed in 11 steps of 2dB from -62 to –42 dB for image-splitting and LEV, in 9 steps of 1dB from -34 to –26 dB for reverberation disturbance and in 11 steps of 1dB from -75 to –65 dB for reverberation perception.

Experiments of four kinds of threshold were performed separately in the order image-splitting, LEV, reverberation perception and reverberation disturbance. For each threshold, 17 sets of stimuli were presented separately to the subject. In a set of stimuli, eleven or nine different stimuli were presented three times in random order. The inter-stimulus interval was 6 s. Thus, each subject made a total of 51 judgements for each stimulus.

In case of the threshold of image-splitting, the mapping method was adopted to avoid the subject being too sensitive to the reverberation signals. Namely, the subject's task was to mark down the direction and the range of the sound image on a circle on the recording sheet for each stimulus after each presentation of stimulus. When the subject perceived multiple sound images, he was requested to mark down all those directions and ranges on the same circle. In analyzing data, it was judged that image-splitting occurred when two ranges of sound images were marked separately on a circle on the recording sheet. In cases of the other thresholds, the subject's task was to answer whether or not, he could perceive each auditory phenomenon after each presentation of stimulus.

Subjects were four male students, 23 years of age ±1 year, with normal hearing sensitivity. Each subject was tested individually while seated, with head fixed in a stationary position in a partially darkened anechoic chamber.

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3.2. Data reduction

The data reduction was done separately for each subject. All thresholds were obtained by using the normal-interpolation process. The process is explained showing an example of the threshold of image-splitting for subject B in Fig. 8. The percentage of image-splitting, that is, the percentage of the observation of multiple sound images was obtained for each stimulus. Z-transformation of those percentages were performed and the regression line and the correlation coefficient were obtained, neglecting data less than 1.0 % and more than 99.0 %. The correlation coefficient was 0.987. This means that the experimental data show the normal distribution. The average value (value at $z = 0$) and its standard deviations (values at $z = \pm 1$) were obtained. The average value means the relative sound pressure level of the first component of reverberation signals to the direct sound, which makes subject B perceive multiple sound images with the probability of 50 %. Therefore, the average value can be regarded as the threshold of image-splitting. The correlation coefficients for all thresholds and for all subjects exceeded 0.928.

3.3. Results and discussion

Figure 9 shows measured values of four kinds of thresholds with their standard deviations together for each subject. There is little difference between individuals for all four thresholds.

First, let us confirm whether or not, the subjects could discriminate between image-splitting and reverberation perception, i. e., whether or not, they could judge image-splitting correctly. For all subjects, image splitting (open circle) is higher than reverberation perception (closed triangle). The difference between them is more than at least 14 dB, and the standard deviations of both thresholds do not overlap. This means that all subjects could discriminate between them, and could judge image-splitting correctly.

Next, let us compare the thresholds of image-splitting and LEV. This is the main purpose of the third experiment. LEV (closed circle) is higher than image splitting (open circle) except for subject A. However, the difference between them is small for any subject. Furthermore, the threshold of LEV is within the standard deviation of image-splitting except for subject B. For subject B, however, the difference between image-splitting and LEV is about 5 dB and nearly equals to that for other subject. From these results, the thresholds of image-splitting and LEV can be considered to be equal. Namely, the listeners begin to perceive LEV, while they begin to perceive image-splitting. This supports the hypothesis that the components of reflections beyond the upper limit of validity for the law of the first wavefront contribute to LEV, since the threshold of image-splitting corresponds to the upper limit. In other words, it is necessary to provide reflections beyond the upper limit in order to make listeners perceive LEV. According to this result, it is not an unaccountable phenomenon that the early reflections contribute to LEV [9]. However, it is a practical solution that late reflections contribute to LEV, since the early reflections seldom exceed the upper limit of validity for the law in room acoustics. On the other hand, this findings is useful to produce LEV in the field of audio-engineering, since the temporal configuration of radiated sound can be designed freely in the field. Note, however, that the result only satisfied the critical condition to support the quantitative relation between LEV and the law of the first wavefront. Needless to say, it is necessary to investigate the quantitative relation more directly. For example, whether or not, the subject perceives the constant quantity of LEV, regardless of the temporal configuration of reflections, when the energy of components of reflections beyond the upper limit of validity for the law of the first wavefront is constant.

Finally, with the relation between the thresholds of reverberation disturbance (open triangle) and LEV (closed circle), the threshold of reverberation disturbance is higher than those of LEV by about 20 dB, and the standard deviations of the thresholds do not overlap. This means that reflections beyond the thresholds of LEV and image-splitting do not always lead to disturbance. In other words, it is possible to make listeners perceived LEV without causing disturbance.

4. Conclusions

A quantitative hypothesis on the relation between spatial impression and the law of the first wavefront was made to clarify what is necessary condition for the perception of ASW and LEV from the point of view of the auditory phenomenon. Three experiments were performed to verify the hypothesis. The results show:
(1) ASW produced by a lateral reflection which exceeds the upper limit of validity for the law is narrower than that produced by a reflection which does not exceeds the upper limit, even if the reflection level is identical.
(2) The upper limit of validity for the law coincides with the relative level of the reflection not exceeding the upper limit, which produces the same ASW as the reflection exceeding the upper limit produces.
(3) The upper limit of validity for the law coincides with the threshold of the perception of LEV.

In conclusion, it seems that the results of three experiments shown in this paper evidence in favor of the hypothesis that the components of reflections under and beyond the upper limit of validity for the law of the first wavefront contribute to ASW and LEV, respectively. Accordingly, it is possible to control ASW and LEV independently by controlling physical factors for each component. The important is that it is necessary to provide reflections beyond the upper limit in order to generate LEV. Furthermore, it is clarified that the reflections beyond the thresholds of LEV do not always lead to disturbance. In other words, it is possible to make the listeners perceive LEV without causing disturbance.

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Table 1 Comparison of [ΔLsp] with [ΔLasw] in dB.

Subject	[ΔLsp]	[ΔLasw]
A	-7.0	-7.0
B	-9.3	-10.0
C	-10.3	-9.7

(dB)

Captions of figures

Figure 1 Schematic explanation of the quantitativehypothesis on the relation between spatial impression and the law of the first wavefront.

Figure 2 Arrangement of loudspeakers (b) used in the first experiment.

Figure 3 Impulse responses of six stimuli used in experiment 1.

Figure 4 Psychological scale of ASW relating to the law of the first wavefront.

Figure 5 Impulse response of stimulus used in experiment 2a.

Figure 6 Impulse responses of the stimuli used in experiment 2b. (a) is the impulse response of the stimulus, the reflection in which exceeds the upper limit of validity for the law. (b) is the impulse response of the stimulus, the reflection in which does not exceed the upper limit of validity for the law.

Figure 7 Loudspeaker arrangement (a) and impulse response (b) used in experiment 3.

Figure 8 Method of data reduction. An example of the subject B for image-splitting.

Figure 9 Four kinds of threshold and their standard deviations. Open circle; image splitting, closed circle; listener envelopment, open triangle; reverberation disturbance, closed triangle; reverberation perception.

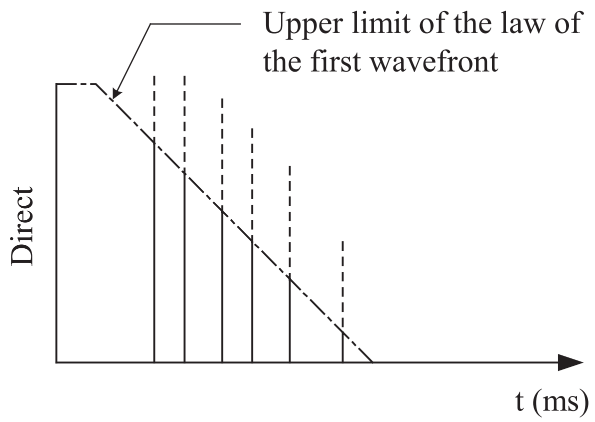

Figure 1

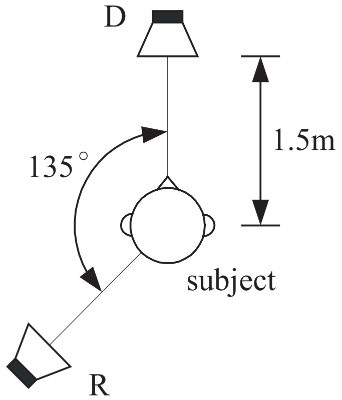

Figure 2

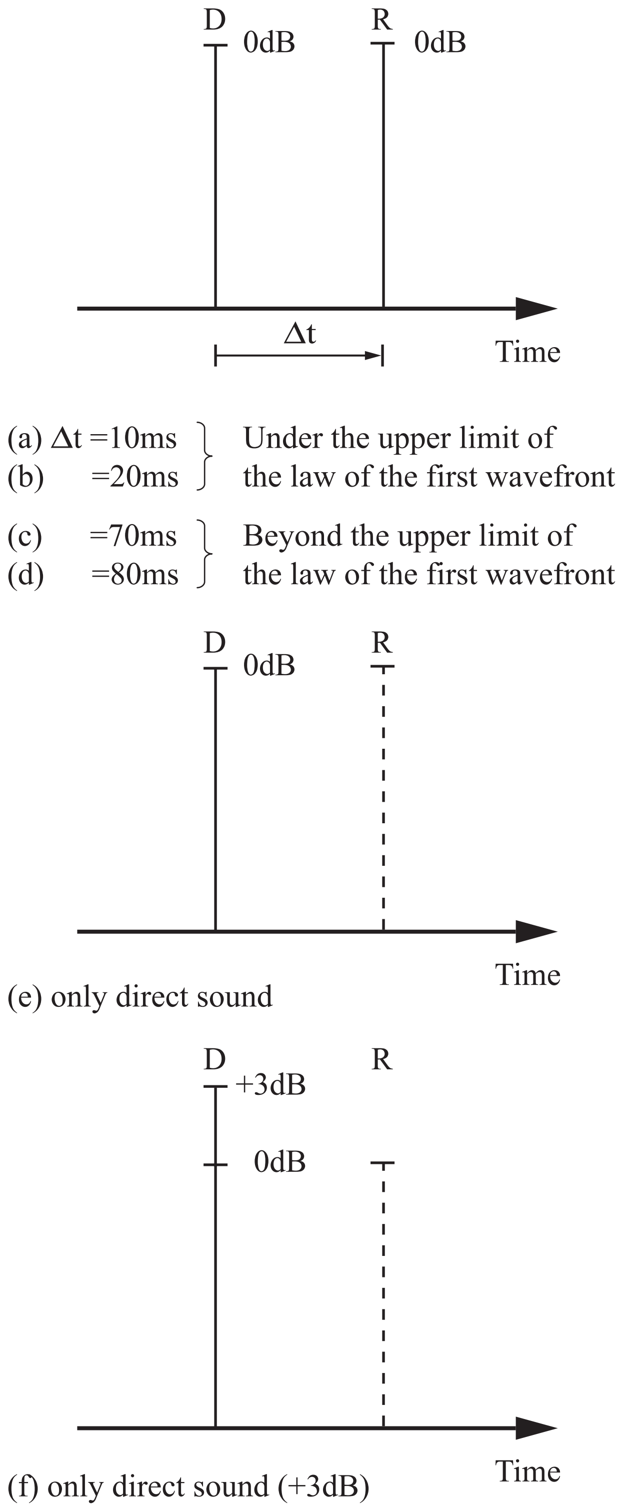
D
0dB
R
0dB
Δt
Time
(a) Δt =10ms
(b) =20ms
Under the upper limit of the law of the first wavefront
(c) =70ms
(d) =80ms
Beyond the upper limit of the law of the first wavefront
D
0dB
R
Time
(e) only direct sound
D
+3dB
0dB
R
Time
(f) only direct sound (+3dB)

Figure 3

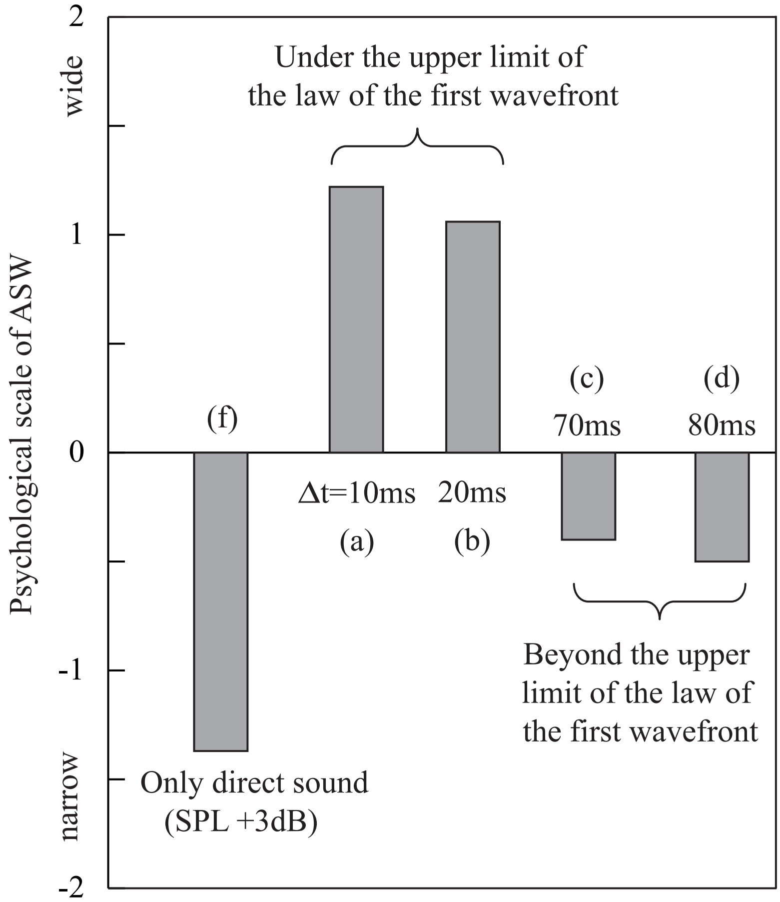
2
1
0
-1
-2
wide
narrow
Psychological scale of ASW
Under the upper limit of
the law of the first wavefront
(f)
Δt=10ms
(a)
20ms
(b)
(c)
70ms
(d)
80ms
Beyond the upper
limit of the law of
the first wavefront
Only direct sound
(SPL +3dB)

Figure 4

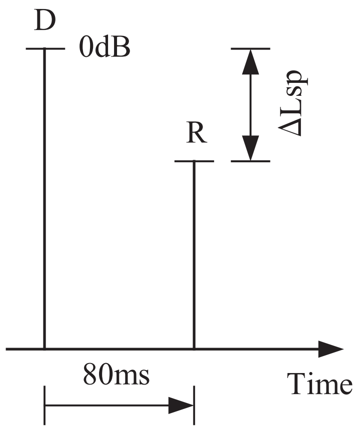

Figure 5

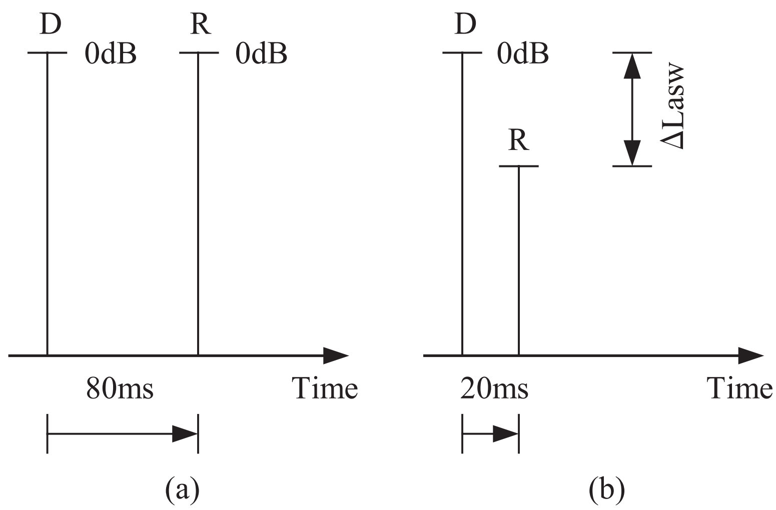

Figure 6

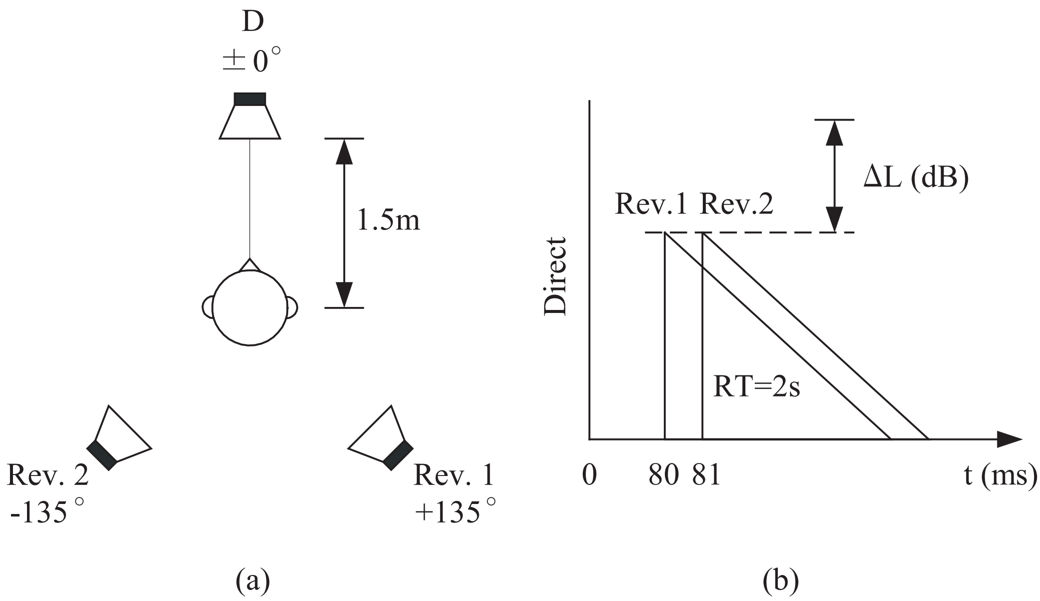
D
± 0°
1.5m
Rev. 2
-135°
Rev. 1
+135°
(a)
ΔL (dB)
Rev.1 Rev.2
Direct
RT=2s
0
80 81
t (ms)
(b)

Figure 7

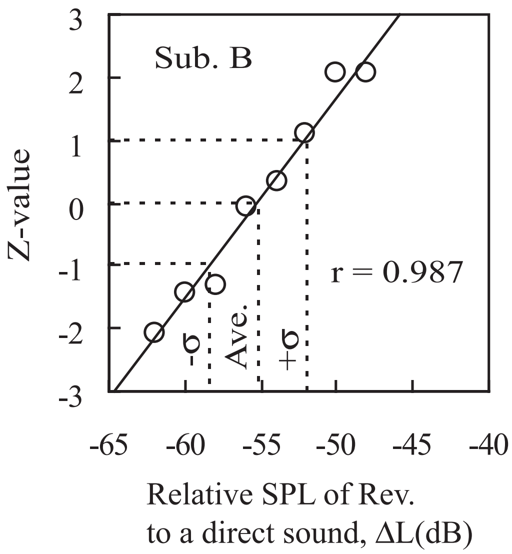
3
2
1
0
-1
-2
-3
Z-value
Sub. B
r = 0.987
-σ
Ave.
+σ
-65
-60
-55
-50
-45
-40
Relative SPL of Rev.
to a direct sound, ΔL(dB)

Figure 8

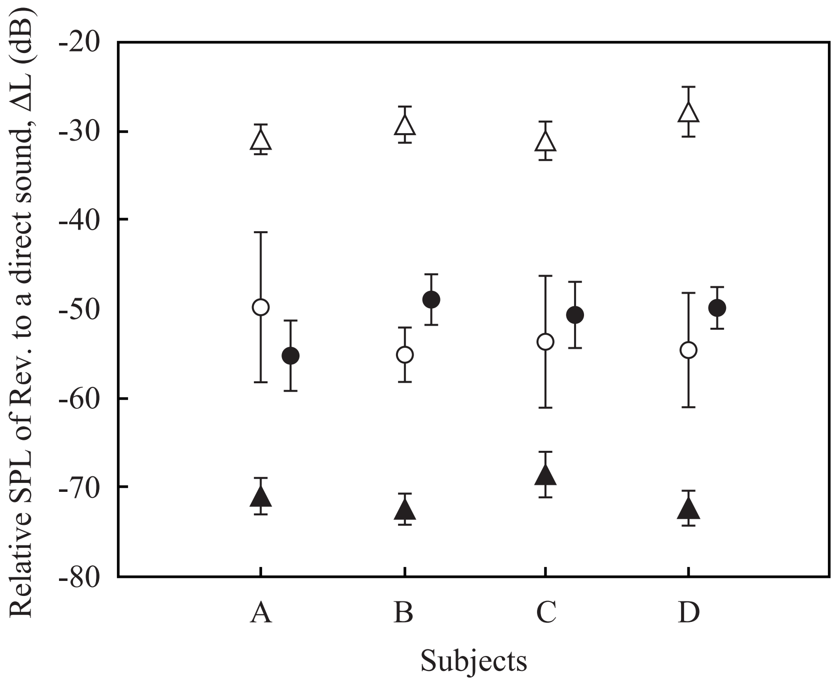
Relative SPL of Rev. to a direct sound, ΔL (dB)
-20
-30
-40
-50
-60
-70
-80
A
B
C
D
Subjects

Figure 9