Proceedings of the Institute of Acoustics

THE RELATION BETWEEN AUDITORY SOURCE WIDTH AND THE LAW OF THE FIRST WAVE FRONT

M. MORIMOTO (1) & K. IIDA (2)

(1)Faculty of Engineering, Kobe University Nada, Kobe 657 JAPAN
(2)Faculty of Engineering, Kobe University and Matsushita Communication Industrial Co., Ltd.
Saedo, Midori, Yokohama 226 JAPAN

1. INTRODUCTION

At the beginning, the authors make clear their standpoint on the acoustical design of concert halls. Figure 1 indicates the evaluation system of a sound field. The acoustic signal s(t) radiated from the sound source is affected by a room transmission function r(t) and arrives at the position of a listener. Then the acoustic signal is expressed as s(t)*r(t). Asterisk denotes convolution. This acoustic signal is affected by head-related transfer functionshlr(t) and arrives at the entrances of both ears as the input signals to the auditory organ. The input signals are expressed as s(t) * r(t) * h lr(t).

Then the listener perceives a sound image which includes various elemental senses. These elemental senses are divided to three kinds of characteristics. The first is temporal one, for instance, reverberant, rhythm, durability and so on. The second is spatial one, for instance, direction, distance, broadening, and so on. The third is qualitative one, for instance, loudness, pitch, timber and so on.Then, the listener subjectively judges each elemental sense, referring to his personal taste. Finally, he has his overall emotional response to the sound with summing subjective judgment to each elemental sense weighted referring to his personal taste again. Therefore, the overall emotional response includes individual differences. On the other hand, the perception of elemental senses does not include the individual difference. According to this system, it is clear that we cannot design the acoustics of concert halls for many and unspecific audience basing on subjective preference, since it is a typical overall emotional response including individual differences [1]. We should design each elemental sense.

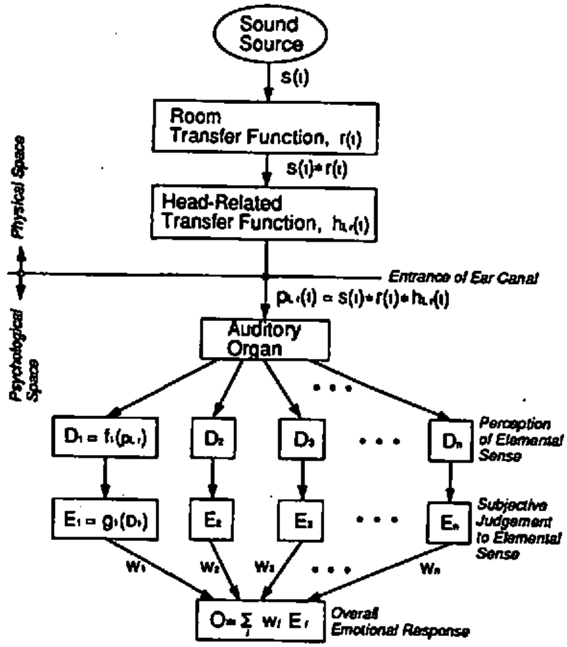


Fig. 1 Subjective evaluation system of a sound field

AUDITORY SOURCE WIDTH

Among of many elemental senses, the spatial attribute, especially broadening is one of the most important characteristics perceived in concert halls. One of the authors has shown that broadening comprises two elemental senses at least [2]. One is auditory source width and the other is feeling of envelopment. Auditory source width (ASW) is defined as the width of a sound image perceived to be fused temporally and spatially with the sound image of a direct sound. Envelopment is defined as the fullness of sound image around a listener, excluding a sound image relating to auditory source width.

In the past, ASW has been studied by many researchers in terms of spatial impression, auditory spaciousness and so on [3]. Well-kr ɔwn physical measures to estimate ASW are lateral efficiency [4] and degree of interaural crosscorrelation [5 - 8]. According to them, ASW increases as the energy of lateral reflection increases. But, the relation between ASW and those physical measures is not yet clear in case that reflections do not satisfy the law of the first wave front, that is, they exceed the upper limit of the law and a sound image splits. Barron and Marshall [4] , who propose lateral efficiency, do not include reflections which cause echo disturbance in calculating lateral efficiency and all researchers, who propose degree of interaural crosscorrelation, have no comment on the relation.

In this paper, how to estimate ASW is investigated, in case that reflections do not satisfy the law of the first wave front. In this paper, hearing experiments were performed in an anechoic chamber using a simple sound field which consists of a direct sound and a single reflection. The music motif used in the experiments is a 7 sec section from the beginning of Partita a-moll fur flûte allein BWV 1013 by J.S.Bach. This motif was played by a musical synthesizer.

2. EXPERIMENT I: COMPARISON OF ASW BY A REFLECTION SATISFYING AND NOT SATISFYING THE LAW OF THE FIRST WAVE FRONT

2.1 Experimental method

Figure 2 shows the loudspeaker arrangement and Fig. 3 shows the impulse response of stimulus. The direct sound was radiated from the front and the reflection was radiated from the horizontal angle of 135 degree on the left side. Six kinds of stimuli were used in this experiment according to the results of the preliminary experiment. Namely, stimuli (a) and (b) completely satisfy the law of the first wave front and (c) and (d) do not at all. The stimuli (e) and (f) consist of only a direct sound. The sound pressure levels of the direct sound and the reflection in stimuli except (f) were equal to each other and the level of the direct sound of 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 a subject's head.

The complete paired comparison test of ASW was carried out. Each subject responded to each pair eight times. Five students served as the subject, who were the same subjects as those in the preliminary experiment.

2.2 Experimental results and discussion

The psychological scale of ASW were obtained using the Thurstone Case V model [9]. But the psychological scale of ASW for the stimulus (e) could not be obtained because all subjects perceived it narrower than ASW for all other stimuli. Figure 4 shows the psychological scale of ASW for stimuli except stimulus (e).

First let us consider ASW for the stimuli (a), (b), (c) and (d). ASW for stimulus (a) and (b) satisfying the law are almost equal to each other. ASW for stimuli (c) and (d) not satisfying are almost equal to each other, too. But the former are wider than the latter. The difference of psychological scale of ASW between them is 1.59 on the average. This means that the probability that the former is wider than the latter is 94% and the probability that the latter is wider than the former is 6%. As a result, ASW for stimulus satisfying the law of the first wave front can be considered clearly to be wider than that for a stimulus not satisfying the law, even if the lateral efficiency or the degree of interaural crosscorrelation is kept constant.

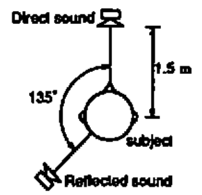


Fig. 2 Loudspeaker arrangement used in Exp I

Next, let us compare the average ASW for the stimuli (c) and (d) with ASW for the stimulus (f). If a reflection which exceeds the upper limit of the law of the first wave front does not contribute to create ASW as a lateral reflection, ASW for those stimuli should be equal, because their sound pressure levels are equal. The former is, however, wider than the latter. The difference of psychological scale of ASW between them is 0.92. This means that the probability that the former is wider than the latter is 82% and the probability that the latter is wider than the former is 18%. As a result, ASW for the stimuli (c) and (d) can be considered clearly to be wider than the stimuli (f). This result suggests that even if a reflection exceeds the upper limit of the law, it contributes to create ASW partially as a lateral reflection.

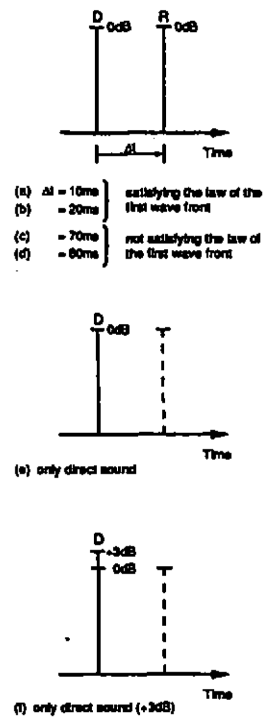


Fig. 3 Impulse responses of six stimuli used in Exp I

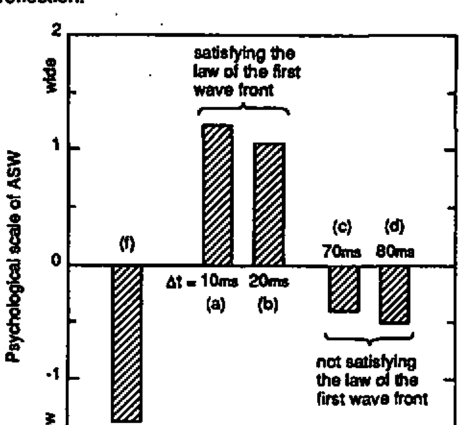


Fig. 4 Psychological scale of ASW relating to the law of the first wave front

3. INVESTIGATION OF METHOD OF ESTIMATING ASW BY A REFLECTION NOT SATISFYING THE LAW OF THE FIRST WAVE FRONT

In this section, a hypothesis on ASW by a reflection which does not satisfy the law of the first wave front is built up and verified by two hearing experiments.

3.1 Hypothesis

Figure 5 shows a sound field which consists of a direct sound D and a single reflection R. The dotted line is the upper limit of the law of the first wave front for the direct sound D. The reflection R exceeds it. The intuitive hypothesis derived from the result of the first experiment is as follows: A part (indicated by a dot-dash line)of a reflection under the upper limit of the law contributes to create ASW as a lateral reflection, when a reflection exceeds the upper limit of the law.

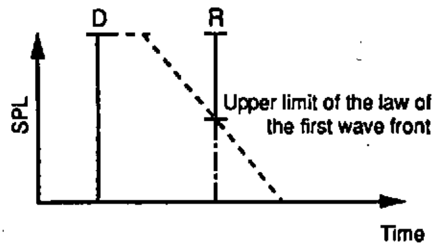


Fig. 5 Schematic explanation of the hypothesis on ASW by a reflection not satisfying the law of the first wave front

3.2 Experimental method

3.2.1 Experiment IIa: The upper limit of the law of the first wave front. The purpose of this experiment was to obtain the upper limit of the reflection level which satisfied the law of the first wave front. The experiment was performed by using the constant method, keeping the time delay of a single reflection constant, and changing the sound pressure level of the reflection.

Figure 6 shows the loudspeaker arrangement and the impulse response of stimulus. The time delay of the reflection was constant at 80 ms. The sound pressure level of the direct sound was constant at 69dBA (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 dB to -15dB.

Each stimulus was presented to each subject fifty times in a random order. The mapping method was adopted to avoid the subject being too sensitive to the reflection. Namely, the subjects' 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 plural sound images, he was requested to mark down all those directions and ranges on the same circle. Three male students served as a subject. They were different from the subjects in the first experiment.

3.2.3 Experiment IIb: ASW by a reflection not satisfying the law of the first wave front. The purpose of this experiment was to obtain the sound pressure level of the reflection satisfying the law which created the same ASW as the reflection not satisfying the law created. The experiment was performed by using the constant method, comparing of ASW by a reflection satisfying and not satisfying the law.

Figure 7 shows impulse responses of the stimuli used in this experiment. The loudspeaker arrangement was the same as in the experiment IIa. According to the result of the first experiment, Figure 7(a) was the impulse response for the stimulus not satisfying 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. Figure 7(b) was the impulse response for the stimulus not satisfying the law, even if the relative sound pressure level of the reflection to the direct sound was 0 dB. The time delay of the reflection was fixed at 20 ms. The relative sound pressure level of the reflection to the direct sound, ΔLasw was changed in eleven steps of 1 dB from -5 dB to -15 dB. The total sound pressure level of the direct sound and the reflection of all stimuli was constant at 71.4 dBA(slow, peak), which was calculated by the equation to obtain binaural summation of loudness [10], using the measured values at the left and the right ear entrances of KEMAR dummy head.

A pair of the stimulus not satisfying the law (Fig. 7(a)) and one of the eleven stimuli satisfying the law (Fig. 7(b)) was delivered. The subject was requested to answer which ASW was wider. Each pair was presented to each subject fifty times in a random order. The same three male students as in the experiment IIa served as a subject.

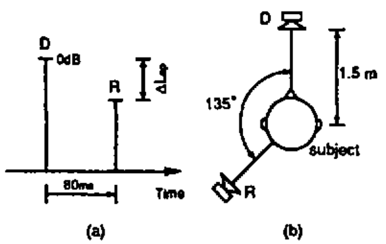


Fig. 6 Impulse response of stimulus (a) and loudspeaker arrangement (b) used in Exp IIa

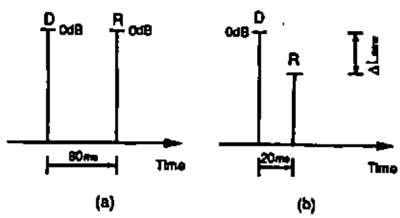


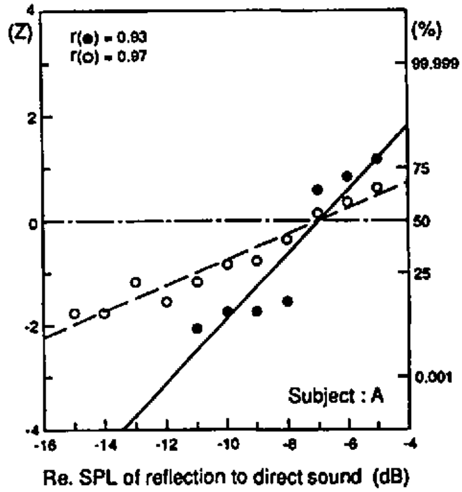
Fig. 7 Impulse responses of stimuli used in Exp IIb

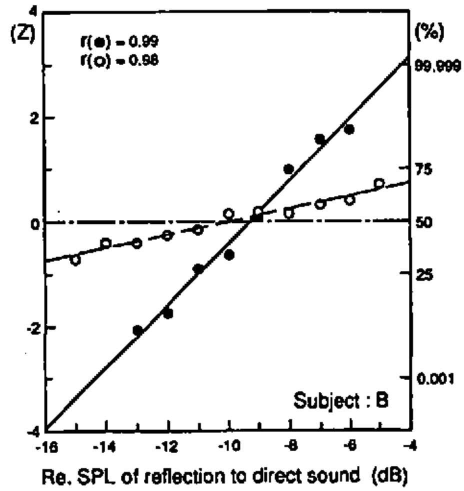
3.3 Experimental results and discussion

The data analysis of both experiments was done separately for each subject. The percentage of split of sound image was obtained from the result of the experiment IIa. And also, the percentage that ASW for a stimulus satisfying the law was wider than ASW for a stimulus not satisfying the law was obtained from the result of the experiment IIb. Furthermore, z-transformations of those percentage were performed and the regression lines and the correlation coefficients were obtained neglecting data of 0 and 100 %. Figure 8 shows the results of experiments IIa and IIb together.

All correlation coefficients in the figures are almost 1.0. This means that all experimental results show normal distribution. The average value was obtained from each regression equation. The average value of the experiment IIa, $\overline{\Delta Lsp}$, is the relative sound pressure level of the reflection to the direct sound which splits a sound image with the probability of 50 %. Namely it is the upper limit of a reflection level which satisfies the law. The average value of the experiment IIb, $\overline{\Delta Lasw}$, means that ASW by the reflection of $\overline{\Delta Lasw}$ which satisfies the law (Fig. 7(b)) is equal to ASW by the reflection which does not satisfy the law (Fig. 7(a)). In other words, it can be considered that the energy of the part of the reflection, which exceeds the upper limit of the law, under $\overline{\Delta Lasw}$ contributes to create ASW, because ASW is independent of the time delay of a reflection [4, 11]

Table 1 shows $\overline{\Delta Lsp}$ and $\overline{\Delta Lasw}$ for each subject. Surprisingly, both values for subject A are identical. The maximum difference between $\overline{\Delta Lsp}$ and $\overline{\Delta Lasw}$ is 0.7 dB for subject B. From these results, it can be concluded that $\overline{\Delta Lsp}$ is equal to $\overline{\Delta Lasw}$. Consequently these results support the hypothesis that a part of the reflection under the upper limit of the law contributes to create ASW as a lateral reflection, when a reflection does not satisfy the law.





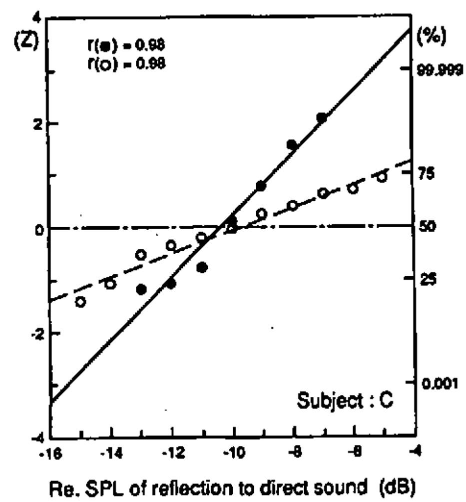


Fig. 8 Probability that a sound image splits (closed circle) and probability that ASW for a stimulus satisfying the law of the first wave front is wider than ASW for a stimulus not satisfying the law (open circle)

Table 1 Comparison of $\overline{\Delta Lsp}$ obtained in Exp IIa with $\overline{\Delta Lasw}$ obtained in Exp IIb

Subject	$\overline{\Delta Lsp}$ (dB)	$\overline{\Delta Lasw}$ (dB)
A	-7.0	-7.0
B	-9.3	-10.0
C	-10.3	-9.7

4. CONCLUSION

The auditory source width (ASW) was investigated under the condition that reflections do not satisfy the law of the first wave front, that is, they exceed the upper limit of the law and a sound image splits. The results of hearing experiments show clearly that:

(1) ASW created by a reflection which does not satisfy the law is significantly narrower than ASW created by a reflection which satisfies the law.

(2) When a reflection does not satisfy the law, a part of the reflection under the upper limit of the law contributes to create ASW as a lateral reflection.

5. ACKNOWLEDGEMENT

The authors wish to thank Mr. H. Kojima and T. Murakami for their cooperation in the experiments.

6. REFERENCES

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