

EFFECTS OF EARLY REFLECTIONS ON LISTENER ENVELOPMENT

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ABSTRACT

It is well known that later reverberant sounds contribute to listener envelopment (LEV). On the other hand, the effect of early reflections on LEV has not sufficiently been clarified. In this paper, listening tests were carried out in order to examine the effects of early reflections on LEV.

As the result, it was confirmed that early reflections affected not only the auditory source width (ASW) but also LEV. In addition, there were some cases in which early reflections suppressed LEV, specifically when the early reflections increased ASW.

INTRODUCTION

It is well known that later reverberant sounds contribute to listener envelopment (LEV)[1]. On the other hand, the effects of early reflections on LEV have not sufficiently been clarified. According to LG[2] which Bradley et al. proposed as an evaluation index of LEV, there is absolutely no effect of early reflections. Early reflections do not completely affect LEV? Moromoto et al. has clarified that not only the front to back ratio(FBR) of the later reverberant sounds but also FBR of early reflections also contribute to LEV[3]. Authors proposed SBTs[4] as an evaluation index of LEV. SBTs indicates that early reflections also affect LEV since SBTs is based on center time(Ts).

The LF[5] is a measure of early lateral reflections. LF is used well when the acoustic quality of a concert hall is evaluated. Supplying early lateral reflections is an important point of view in the acoustical design of the concert hall. It is understood today that LF is the evaluation index of the auditory source width (ASW)[6]. LF can be controlled in the arrival direction of the early reflections and the level of the early reflections. In this paper, listening tests were carried out in order to examine how the arrival direction and the level of the early reflections, respectively, influence LEV.

METHOD

Two experiments were conducted using a simulated sound field in an anechoic chamber. We installed 16 loudspeakers, which were 1.5m apart from the listeners at equal intervals of 22.5

degrees in a horizontal plane including the two ears of a listener. When carrying out the experiments, we selected the required number of loudspeakers from among the sixteen and reproduced direct sound or reverberant sounds.

We used the virtual sound source distribution that produced the basic sound field shown in Fig. 1 in our experiments. The reverberation time of the basic sound field was about two seconds and C80 was 0.5dB, while Lf was 0.2 and LG was 2.1dB. First, the virtual sound source distribution was divided into the early reflections which is up to 80ms and the late reflections which is after 80ms. Next, the early reflections up to 80ms were divided into two parts, the left and right. The late reflections after 80ms were horizontally divided into eight parts. Third, the directional responses required for reproduction were synthesized from the virtual sound source of each part. As a result, two early responses and eight late responses were prepared. As a stimulus, we used a sound composed of the directional response waveform convolved with a portion of the first movement which was a Mozart divertimento about ten seconds long.

The experiments were conducted according to Scheffe's paired comparison method[7]. Each pair of sound fields was randomly presented. Nine subjects rated the LEV and ASW of the second sound field of each pair on a seven-point scale in comparison with the first one. Previous to the experiments, we explained to the subjects the differences between LEV and ASW, and made sure they understood the possibility of change in a variety of auditory senses (such as reverberance and loudness).

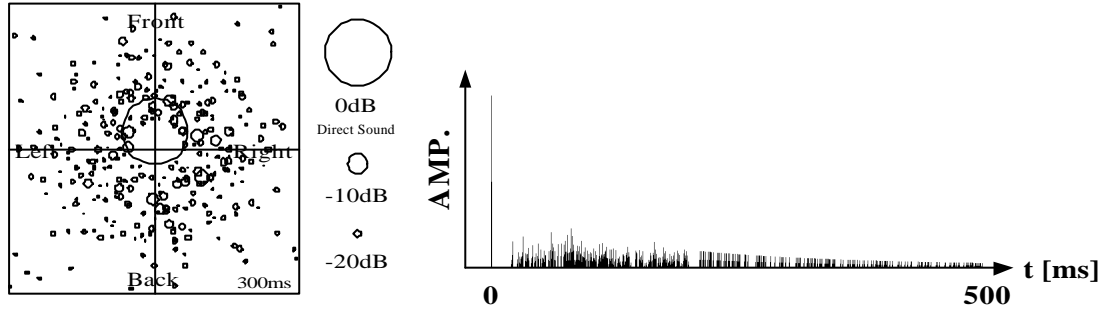


Fig. 1.- Virtual sound source distribution and impulse response of the basic sound field

DEFINITION OF SBTs AND LTs

SBTs(Spatially Balanced Ts)

SBTs is based on center time (T_s). First, we newly defined T_{s_i} as indicated in Formula 1 below. The difference between T_s and T_{s_i} is the numerator in their formula. The numerator in the T_{s_i} formula is a directional response in each direction. T_{s_i} means the contribution of individual directional responses in direction i to T_s . Therefore, the total of T_{s_i} becomes T_s .

$$T_{s_i} = \int_0^{\infty} t \cdot p_i^2(t) dt / \int_0^{\infty} p^2(t) dt \quad (1)$$

Where, $p(t)$: omnidirectional impulse response, $p_i(t)$: reflections arriving from direction i or directional responses in direction i .

Next, we corrected T_{s_i} , as indicated in Formula 2, taking the contribution of the direction of arrival to LEV into account.

$$a_i = T_{s_i} \cdot (1 + \cos \hat{\alpha}_i) / 2 \quad (2)$$

Where, a_i : level, time and direction factors of reflections arriving from direction i , $\hat{\alpha}_i$: angle from binaural axis. In addition, the value of $(1 + \cos \hat{\alpha}_i) / 2$ in Formula 2 reaches a maximum in the binaural axis direction and changes so that it does not become zero in the front/back direction. This is because the contribution of frontal reflection is not zero in our previous experiment[4].

We quantified the mutual effects of the two reflections by multiplying their respective values in order to quantify the spatial distribution of the reflections. We arranged it so that the arrival direction of the two reflections would contribute more to LEV as the angle between them increased. Furthermore, since the contribution of a certain reflection to LEV is influenced by all other reflections, we decided to integrate all mutual effects of the other reflections. These are expressed by Formula 3 below.

$$b_i = a_i \cdot \sum_{j=0}^n a_j \cdot \sin(\mathbf{q}_{ij}/2) \quad (3)$$

Where, b_i : contribution of reflection $p_i(t)$ to LEV, \mathbf{q}_{ij} : angle between directions of arrival i and j .

Finally, as indicated in Formula 4 below, we integrated the mutual effects b_i of all reflections and considered that to be the overall contribution SBTs (spatially balanced Ts) to LEV.

$$SBTs = \sqrt{\sum_{i=0}^n b_i} = \sqrt{\sum_{i=0}^n \sum_{j=0}^n a_i \cdot a_j \cdot \sin(\mathbf{q}_{ij}/2)} \quad (4)$$

SBTs quantifies the temporal and spatial balance of the reflections using center time. It is possible to consider SBTs to be an extension of center time taking into consideration the spatial balance of the reflected sound. SBTs increases when the arrival directions are distributed over a wide range. And high SBTs is achieved when the arrival directions and the levels of the reflections are spatially balanced. These characteristics of SBTs are the same as the LEV scores obtained in our previous experiment[4].

LTs(Lateral Center Time)

We newly defined LTs(lateral center time) as indicated in Formula 5 below.

$$LTs = \int_0^{\infty} t \cdot p^2_L(t) dt / \int_0^{\infty} p^2(t) dt \quad (5)$$

Where, $p(t)$ is the omni-directional impulse response and $p_L(t)$ is the instantaneous pressure response of the lateral energy measured using a figure-of-eight microphone with its sensitive lobes pointing to either side of the listener.

As well as SBTs, the advantage of LTs is to consider not only the reflected sound energy but also the time parameter. LTs does not need the distinction (like 80ms) in the initial stage and the later stage. In addition, LTs can be comparatively simply measured using a figure-of-eight microphone, while SBTs needs directional responses measured by the directional microphone.

However, though the effect of the arrival direction of the reflections can be evaluated using LTs, the effect of the spatial distribution of reflections on LEV cannot be sufficiently evaluated, since the mutual effects of a pair of the reflections is not considered. Therefore, the accuracy of SBTs is higher than LTs on the evaluation of LEV. LTs is consistently the approximate value of SBTs. Both LTs and SBTs are affected by early reflections.

EXPERIMENT 1

We have conducted a psychological experiment in order to investigate the influence of early reflections energy on LEV.

Experimental Condition

Four sound fields were used in this experiment. The level of early reflections within 80ms varied from 0dB to 9dB at equal intervals of 3dB relative to the basic sound field. The C80 of each sound field were as follows: 0.5dB, 2.6dB, 4.6dB, 7.1dB. Only the early reflections level varied so that the direct sound level and later reverberant sounds after 80ms were kept constant. Therefore the listening levels of each sound field became as follows: 72.0, 73.7, 76.0, 78.5dBA.

In this experiment we used eight loudspeakers located at equal intervals of 45 degrees on the horizontal plane as shown in Fig. 2. The front loudspeaker radiates direct sound and later reverberant sound. The loudspeakers located at ± 45 degrees, straight ahead of the listener,

radiate early sounds and later reverberant sounds. The other loudspeakers radiate only later reverberant sounds.

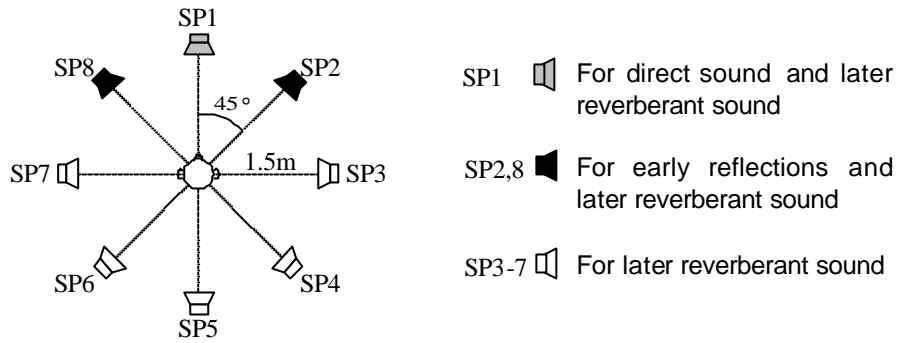


Fig. 2.- Loudspeaker arrangement in Experiment 1

Results and Discussion

Results of this experiment are shown in Fig. 3. Notice in these figures, ASW increases as the level of early sound increases. On the other hand, LEV decreases as the level of early sound increases. And these changes were almost rectilinear.

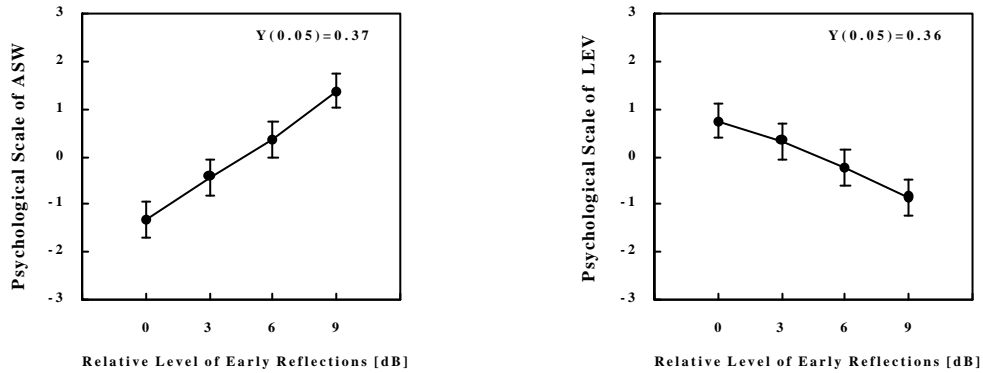


Fig. 3.- Psychological scale of Experiment 1

LF, SBTs and LTs of each sound field for Experiment 1 are shown in Fig. 4. The LF increases as early sound level increases. This is correspondent to the change in ASW. On the other hand, SBTs and LTs decrease as early sound level increases. They are correspondent to the change in LEV.

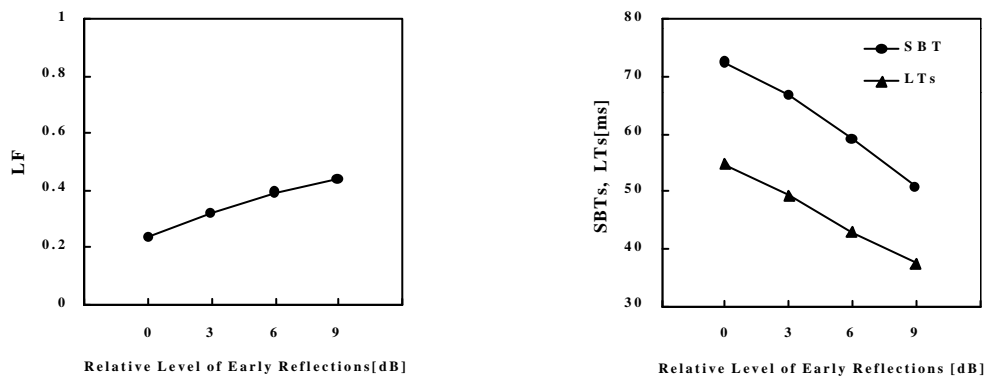


Fig. 4.- LF, SBTs and LTs of each sound field for Experiment 1

As the result, it was confirmed that early reflections affected not only ASW but also LEV. In addition, there was a case in which early reflections suppressed LEV, specifically when the level of early reflections increased. In such a condition, the change of ASW and LEV is the contrariety.

EXPERIMENT 2

We have conducted a psychological experiment in order to investigate the influence of the arrival direction of early reflections on LEV.

Experimental Condition

In this experiment, four sound fields were used. The early sound level of the used sound field was 3dB higher than the basic sound field. As shown in Fig. 5, the arrival direction of early reflections changed with 22.5, 45.0, 67.5 and 90.0 degrees straight ahead of the listener. The late reverberant sounds were radiated from eight loudspeakers located at equal intervals of 45 degrees on the horizontal plane. The C80 (2.6dB) and the listening level (72dBA) of all the sound fields were kept constant.

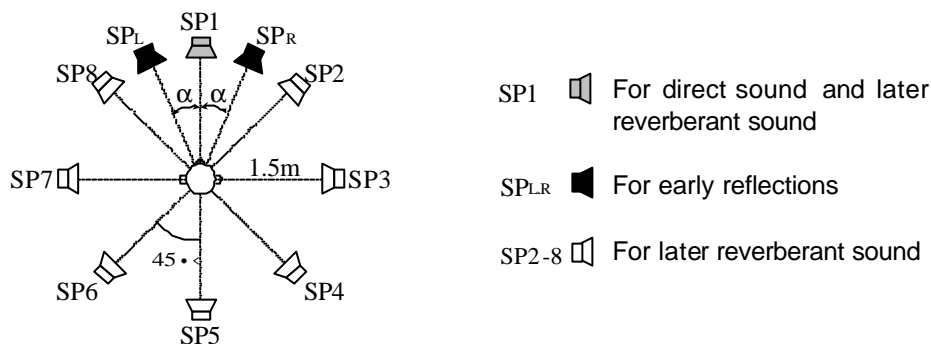


Fig. 5.- Loudspeaker arrangement in Experiment 2

Results and Discussion

Results of this experiment are shown in Fig. 6. Based on these results, both ASW and LEV increased, as the arrival direction of early reflections move from the front to the side. Both changes of ASW and LEV are similar to the cosine curve. There is no significance on both ASW and LEV between 67.5 and 90 degrees, when it is observed in more detail. Especially, the change of LEV is generally small, and the significance occurs between 22.5 degrees and the other condition.

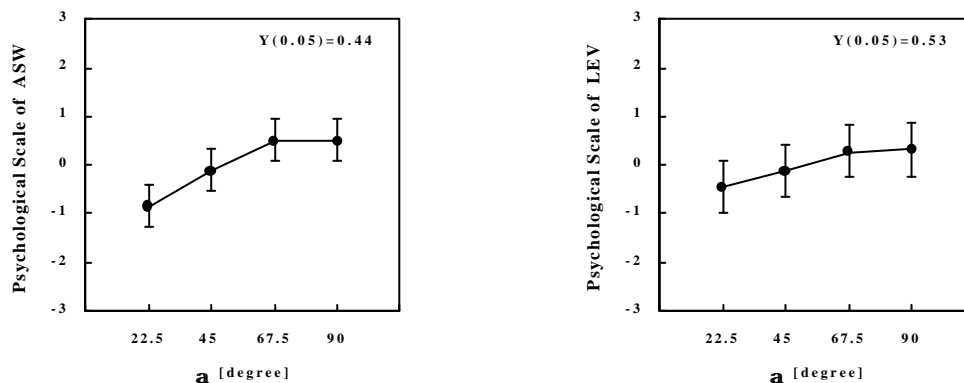


Fig. 6.- Psychological scale of Experiment 2

LF, SBTs and LTs of each sound field for Experiment 2 are shown in Fig. 7. Based on these results, all indexes increase, as the arrival direction of early reflections move from the front to

the side. The changes of all indexes indicate the cosine curve. These are correspondent to the changes of ASW and LEV in this experiment.

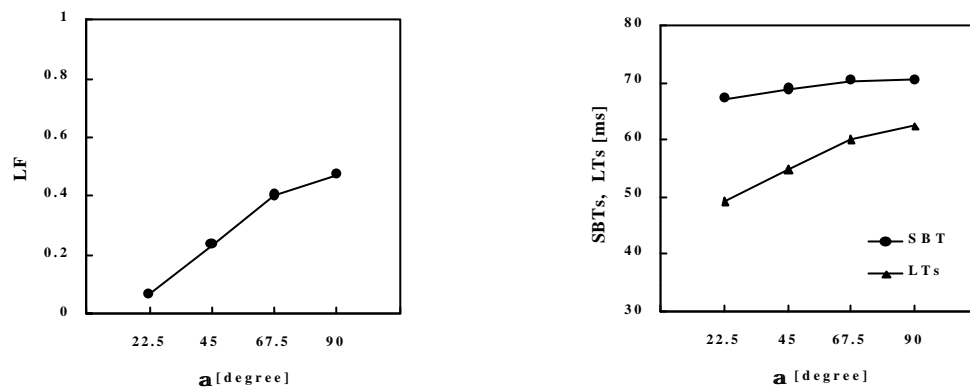


Fig. 7.- LF, SBTs and LTs of each sound field for Experiment 2

In the present experiment, the increase of LEV was small. The change of SBTs is also small. Therefore, the contribution of early reflections to LEV may not be more remarkable than the late reverberant sounds. However, LEV did not decrease, when the LF increased by moving the arrival direction of early reflections to the side. This is different from the phenomenon where LF increases when the level of lateral reflections increases. In the case of the acoustical design which increases the LF by moving the arrival direction of early reflections to the side, it was proven that both ASW and LEV increase.

CONCLUSION

It was confirmed that early reflections affected not only ASW but also LEV. Especially, it was proven that level and the arrival direction of early reflections have different effects on LEV. LEV increased, as the arrival direction of early reflections move from the front to the side. On the other hand, LEV decreased as the level of early sound increased. Such changes could be evaluated by both the SBTs and LTs.

LF is used well when the acoustic quality of a concert hall is evaluated. Supplying early lateral reflections is an important point of view in the acoustical design of the concert hall. LF is the correspondent to ASW in the present experiments. However, in the acoustical design that controlled only the LF, LEV might be adversely suppressed even in the condition in which ASW increases. This is because there were some cases in which LEV was suppressed, specifically when the level of early reflections increased.

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