

PAPER

Effects of arrival direction of late sound on listener envelopment

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Abstract: Two kinds of psychological experiments are conducted to reconfirm the effect of late sound from directions other than lateral on LEV, which was reported in our previous paper, and to clarify the degrees of contribution of directional late energy to listener envelopment (LEV). In the first experiment, the levels of late sound arriving from four directions, namely, lateral, frontal, overhead, and back, are independently varied. The results reconfirm that not only the lateral level, but also the levels of late sound from above and behind the listener affect LEV significantly. In the second experiment, directional late energy ratios are varied keeping the total level of late energy constant. The results indicate the degrees of contribution of lateral, overhead, and back late energy to LEV.

Keywords: Listener envelopment, Directional late energy ratio, Psychological experiment

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1. INTRODUCTION

Spatial impression represents one of the most important psychological factors which help to evaluate the sound fields of concert halls. Morimoto and Maekawa [1] and Bradley and Soulodre [2] demonstrated that spatial impression consists of at least two aspects, namely, the auditory or apparent source width (ASW) and listener envelopment (LEV). The former is defined as the width of a sound image fused temporally and spatially with a direct sound image. The latter is defined as the listener's sensation when the surrounding space is filled with sound images other than a sound image composing ASW. Some related works [3-5] have shown that ASW is mainly influenced by early lateral reflections and that LEV is predominantly produced by late-arriving lateral reflections.

With such a background, the subjective effect of reflections arriving from directions other than lateral has hardly been investigated up to the present time, except for a few works [6,7]. Therefore, the spatial effect in three-dimensional sound fields, in which listeners are exposed to the reflections coming from various directions with a

vertical energy component, has not yet been clarified. In addition, this means that limits on the application of the indices proposed as predictors of LEV have been left obscure until now. A fundamental examination, using sound fields with reflections arriving not only from a horizontal direction but also from a vertical direction, is necessary in order to grasp the subjective mechanism of the listener envelopment perceived in a three-dimensional enclosure.

The major concern here originates from the simple question of whether or not listener envelopment, an acoustical sensation in three-dimensional space, is created by lateral sound energy alone, although it is accepted that LEV is strongly related to late-arriving lateral energy. The basic goals of this study, therefore, are to investigate the effect of the directional energy components of late sound on LEV and to clarify an objective measure for the prediction of LEV by taking every factor into consideration.

In our previous work [8], it was shown that the late sound levels from above and behind the listener, as well as from the lateral direction, correlate to LEV positively and strongly, and that not only late lateral sound, but late sound from other directions such as overhead, back, and frontal,

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also contributes to the perception of LEV to a greater or lesser degree.

In acoustic design of actual auditoria, the architectural conditions for obtaining the lateral reflections enough to produce LEV are not necessarily satisfactory because of some restrictions for architectural planning. Suppose that late sounds from directions other than lateral are also effective for LEV, the incorporation of non-lateral late sounds, e.g. from above and behind the listener, into the design policy for LEV enables us to compensate for lack of LEV in the situation mentioned above. In other words, if the degree of contribution of late sounds from directions other than lateral to LEV is clarified, we can have more options and possibilities in the design method for LEV by considering the degree of contribution of them than in the method with only lateral reflections.

The next question is how the late sound from directions other than lateral contributes to LEV. Namely, the degree of effects of late sound arriving from four directions should be quantitatively cleared. In our previous paper, however, the effects of four directional late levels on LEV were not comparable, because the tests were performed separately according to four arrival directions of late sound and the experimental conditions of listening sound pressure level and early-to-late sound energy were not strictly fixed. Therefore, in this paper two kinds of psychological experiments, in which the preceding four tests are combined, are conducted with simulated sound fields in order to reconfirm the effect of late sound from directions other than lateral on LEV and to clarify the degrees of contribution that the directional late energy makes to LEV. Firstly, in Experiment 1, the effect of level changes in late sound arriving from four directions, namely, lateral, frontal, overhead, and back, on perceived LEV is investigated keeping the listening level constant. Secondly, in Experiment 2, the effect of directional late energy ratios on LEV is investigated keeping the listening level and the total level of late sound constant.

2. METHOD

2.1. Apparatus

Figure 1 shows the arrangement of the loudspeakers in an anechoic chamber. The sound fields consisted of monophonic direct sound, six discrete early reflections derived from multi-tap delay machines, and later sound added by digital reverberators. A loudspeaker for direct sound was in front of the listener, while two loudspeakers for early reflections were placed symmetrically at azimuth angles of $\pm 45^\circ$ relative to the direct sound source on the horizontal plane of the listener's head. Late sound, arriving more than 80 ms after the direct sound, was fed through five loudspeakers. Four of the loudspeakers were located at azimuth angles of $\pm 90^\circ$ (left and right), 0° (front), and 180°

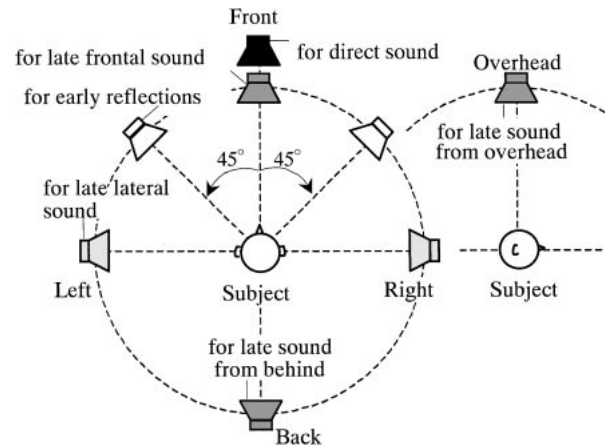


Fig. 1 Arrangement of loudspeakers in an anechoic chamber.

(back) on the horizontal plane. The fifth, a vertical loudspeaker, was located at an elevation angle of 90° just above the listener. In this way, a total of five loudspeakers for late sound were arranged to individually control three orthogonalized directional components of late sound energy. They had lateral, longitudinal, and vertical components, which presented the fundamental spatial distribution of late energy. All the loudspeakers were equidistant (1.5 m) from the listener. The reverberation times were 2.14 ± 0.05 , 2.13 ± 0.09 , 1.91 ± 0.08 , 1.84 ± 0.02 , 1.86 ± 0.02 , 1.70 ± 0.05 , and 1.17 ± 0.02 s at the seven octave bands from 125 to 8 kHz, respectively. The average reverberation time was set at 1.8 s in all tests.

2.2. Procedure

A method of paired comparisons was employed for all tests. An anechoic recording of the 10 s section of Bizet's 'L'Arlesienne, Suite no. 2, Menuetto' (bars 15–18) was used as the music motif. Pairs of stimuli, consisting of two different sound fields with an interval of 1 s between them, were used. All the sound field pairs, followed by an interval of 5 s, were presented to the subjects in random order. The reproduction of the sequence program was automatically controlled by a personal computer with a MIDI-interface. The subjects were students, 22 to 26 years old, with normal hearing sensitivity. The term 'listener envelopment' was explained to the subjects prior to the experiments using a conceptual illustration and some comments which expressed the above-mentioned definition of LEV. A preliminary practice session was held in order to ensure that the subjects were familiar with the requirements of each test. Each subject, seated with his/her head fixed, was individually required to judge the difference in perceived LEV between each pair of sound fields. Namely, the subjects judged whether the LEV of the second stimulus was weaker or stronger than that of the preceding one in a pair of sound fields.

2.3. Psychological Analysis

In both experiments, psychological interval scales of LEV were constructed from the experimental results by the method in Thurstone's Case V [9]. This method is an approximation used to solve equations in Thurstone's law of comparative judgment. A 'psychological interval scale' means a subjective distance between two stimuli, S_i and S_j , when a probability density of the response for each stimulus is assumed to be normally distributed. A psychological interval corresponding to 'just noticeable difference', subjective jnd, is approximately 0.68 on this scale, the value of which can be calculated when the probability of judgment for $S_i > S_j$ is equal to 75%.

2.4. Physical Parameters

Four directional late sound levels and four directional late energy ratios were calculated from the overall impulse responses obtained with omni-directional, figure-of-eight, and dummy-head microphones in order to determine the spatial distribution of the late-arriving sound energy. In Experiment 1, late lateral sound level LL_{late} , late frontal sound level FL_{late} , late overhead sound level VL_{late} , and late back sound level BL_{late} were defined as the relative levels of each directional late energy to the direct sound energy, which was held constant in all tests. In Experiment 2, late lateral energy ratio LE_{late} , late frontal energy ratio FE_{late} , late overhead energy ratio VE_{late} , and late back energy ratio BE_{late} were defined as ratios of each directional late energy to the total energy of the late sound. The listening sound pressure level was measured using a dummy-head microphone for the music source. The A-weighted binaural SPL [10] ($BSPL$) was calculated with the equation to obtain a binaural summation of the loudness of the sound fields, using the measured levels (time constant: slow) at the left and the right ears of the dummy-head.

3. EXPERIMENT 1

The object of the first experiment was to investigate the individual effect of four directional levels of late sound, namely, lateral, frontal, overhead, and back, on perceived LEV, using sound fields for which the late sound level from each direction was independently varied.

3.1. Experimental Conditions

The structure of the sound fields is diagrammatically shown in Fig. 2. The delay times and the levels of both direct sound and early reflections were fixed in all tests. The relative levels of early reflections to the direct sound were adjusted so that LF_{80} was 0.17.

As given in Table 1, seven sound fields were used in Experiment 1. In stimulus no. 1, the four directional late levels were set to be equal. In stimuli nos. 2 and 3, only LL_{late} was varied over a range of approximately 8 dB based

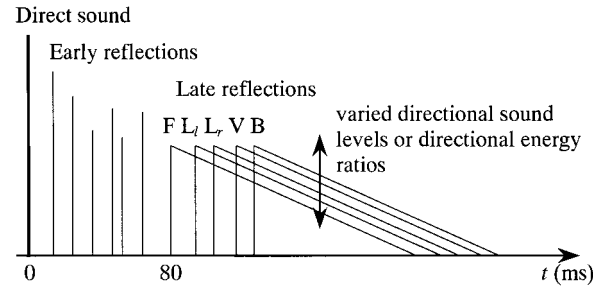


Fig. 2 Structure of the sound fields used in the experiments (F = frontal, L = lateral, V = overhead, and B = behind; subscripts l and r : left and right). In experiment 1, each directional late level is independently varied. In experiment 2, directional late energy ratios are varied keeping the total level of late sound constant. The frontal energy ratio is fixed in all stimuli.

Table 1 Seven sound fields used in experiment 1.

| Stimulus no. | $BSPL$ (dB) | C_{80} (dB) | Directional late sound levels (dB) | | | |
|--------------|-------------|---------------|------------------------------------|--------------------|--------------------|--------------------|
| | | | LL_{late} | FL_{late} | VL_{late} | BL_{late} |
| 1 | | 2 | -3.6 | -3.3 | -3.9 | -3.3 |
| 2 | | 0 | 1.0 | -3.8 | -3.8 | -3.7 |
| 3 | | -2 | 4.8 | -3.5 | -4.0 | -3.2 |
| 4 | 63 | 0 | -3.0 | -3.6 | 0.3 | -3.7 |
| 5 | | -3 | -3.3 | -3.4 | 4.2 | -3.2 |
| 6 | | -3 | -3.1 | 4.5 | -3.7 | -3.5 |
| 7 | | -2 | -2.9 | -3.6 | -3.9 | 5.1 |

on stimulus no. 1. Similarly, only VL_{late} was varied in stimuli nos. 4 and 5, only FL_{late} was varied in stimulus no. 6, and only BL_{late} was varied in stimulus no. 7. In this way, the directional energy, except for the changed directional sound, was kept almost constant. Therefore, the late lateral levels were almost equal among stimuli nos. 1, 4, 5, 6, and 7. The ratio of early-to-late sound energy, C_{80} , was in the range of -3 to 2 dB. All combinations of seven stimuli, namely, twenty-one pairs, were presented to six subjects. Each subject was tested individually to judge each pair of stimuli eight times, and thus, a total of 168 judgments were made. The $BSPL$ with the music source was constant at 63 dB for all stimuli at the listening point.

3.2. Results and Discussion

The subjects' ability to discriminate between sound fields was statistically significant at a level below 5%, and the standard of judgment was agreed upon by all subjects at a level below 5% of significance. The results of conformity tests with the Thurstone Case V model showed that the experimental data was significant at a level below 1%. The psychological interval scales of LEV versus LL_{late} , FL_{late} , VL_{late} , and BL_{late} are plotted in Figures 3(a)–(d), respectively. As mentioned above, the significance of the

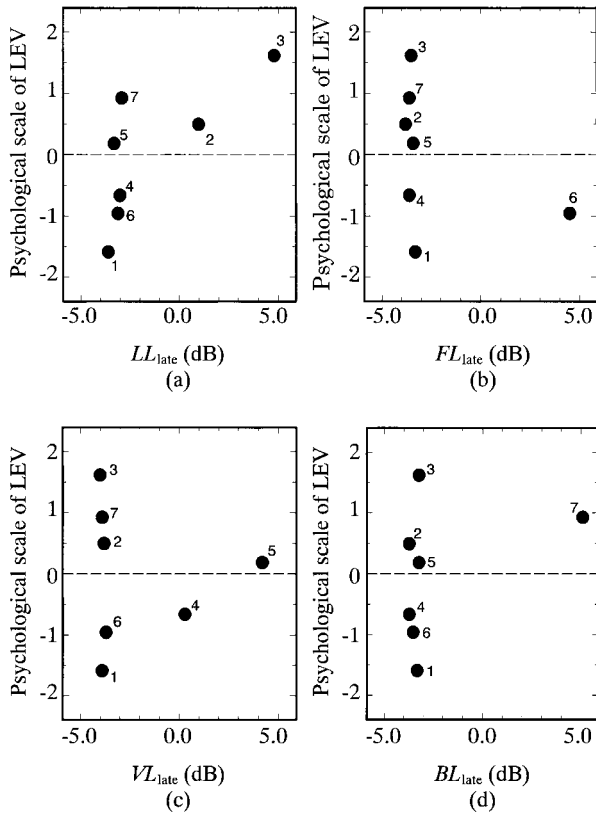


Fig. 3 Psychological scale of LEV versus four directional late levels in experiment 1. The subscript indicates the stimulus no.

difference in LEV is discussed on the basis of the jnd of LEV.

Firstly, let us consider the effect of changes in the late lateral sound level. Figure 3(a) shows that LEV clearly becomes stronger with an increase in LL_{late} . Namely, the maximum difference in LEV between stimuli nos. 1 to 3 is 3.21, corresponding to a change of 8 dB in LL_{late} . This difference exceeds the jnd of 0.68. This means that LL_{late} significantly affects LEV, as is generally accepted. Furthermore, the LEVs for stimuli nos. 4 to 7 are also stronger than that for stimulus no. 1. The differences in LEV between stimuli nos. 1, 4, 5, and 7, exceed 0.68. In other words, the subjective changes in LEV are distinctly perceived for stimuli nos. 1, 4, 5, and 7, even though the late-arriving lateral energy does not change for them.

Next, let us consider the effect of the late sound levels from directions other than lateral. Figures 3(c) and (d) show that LEV becomes stronger with increases in VL_{late} and BL_{late} . The difference in LEV between stimuli nos. 1 and 5 is 1.77, corresponding to a change of 8 dB in VL_{late} . The difference in LEV between stimuli nos. 1 and 7 is 2.52, corresponding to a change of 8 dB in BL_{late} . Both differences exceed 0.68. This means that VL_{late} and BL_{late} significantly affect LEV. In addition, as shown in Fig. 3(b), the difference in LEV between stimuli nos. 1 and 6 (0.63)

Table 2 Result of multiple regression analysis between perceived LEV and four directional late levels in experiment 1, significant at $p < 0.05$.

| Multiple correlation coefficient | Standard regression coefficients | | | |
|----------------------------------|----------------------------------|--------------------|--------------------|--------------------|
| | LL_{late} | FL_{late} | VL_{late} | BL_{late} |
| 0.991 | 1.088 | 0.112 | 0.518 | 0.726 |

is not psychologically significant, corresponding to a change of 8 dB in FL_{late} .

Furthermore, a multiple regression analysis was done to investigate the degree of contribution of each directional late level to the perceived LEV. A psychological interval scale for LEV was used as the criterion variable, while the four directional late levels were used as explanatory variables, which were quite independent of each other. Table 2 shows the standard regression coefficients, which express the contribution of four variables to LEV. A variance test ensured that the results were significant at a level below 5%. The multiple correlation coefficient is 0.991. The standard regression coefficient is the highest for LL_{late} and the lowest for FL_{late} . Since the coefficients for VL_{late} and BL_{late} are 48 and 67 percents of that for LL_{late} respectively, the results indicate that they also affect the perceived LEV.

From these discussions, it is reconfirmed that not only the late lateral sound level, but also the late sound levels from directions other than lateral affect LEV. Furthermore, late lateral sound has the largest effect on LEV, while the degrees of contribution of late sound level from above and behind the listener are more than about 50 percent of that of lateral sound level. And, the degrees of contribution of them to LEV increase in order of lateral, back, overhead, and frontal.

4. EXPERIMENT 2

In the preceding experiment, the total level of late sound was not constant, because only the late sound level from one direction was independently varied. In Experiment 2, the relation between the directional late energy ratios and LEV is investigated keeping the total level of late sound constant.

4.1. Experimental Conditions

As shown in Fig. 2, the structure of impulse responses and the conditions of direct sound and early reflections were quite similar to those used in Experiment 1. The directional late energy ratios, LE_{late} , VE_{late} , and BE_{late} were changed keeping the total level of late sound constant. The frontal energy ratio, FE_{late} , was fixed at 0.10 throughout the tests. Experiment 2 consisted of three separate tests, namely, Experiments 2(a), (b), and (c), according to the

Table 3 Seven sound fields used in experiment 2.

| Stimulus no. | $BSPL$ (dB) | Directional late sound energy ratios | | | |
|--------------|-------------|--------------------------------------|-------------|-------------|-------------|
| | | LE_{late} | VE_{late} | BE_{late} | FE_{late} |
| 1 | 63 | 0.30 | 0.30 | 0.30 | 0.10 |
| 2 | | 0.25 | 0.60 | 0.05 | 0.10 |
| 3 | | 0.25 | 0.10 | 0.55 | 0.10 |
| 4 | | 0.60 | 0.25 | 0.05 | 0.10 |
| 5 | | 0.10 | 0.25 | 0.55 | 0.10 |
| 6 | | 0.60 | 0.10 | 0.20 | 0.10 |
| 7 | | 0.10 | 0.60 | 0.20 | 0.10 |

value of C_{80} which was set at -3 , 0 , and $+3$ dB. As given in Table 3, seven kinds of sound fields were used in each test. In stimulus no. 1, LE_{late} , VE_{late} , and BE_{late} were set at 0.30. In stimuli nos. 2 to 7, they were varied in three steps over a range of 0.05 to 0.60, referring to the measured values in auditoria [11]. All combinations of seven stimuli, namely, twenty-one pairs, were presented to eight subjects. Each subject was tested individually to judge each pair of stimuli eight times. The $BSPL$ was constant at 63 dB.

4.2. Results and Discussion

The results of conformity tests with the Thurstone Case V model showed that the experimental data was significant at a level below 1%. The psychological interval scales for LEV are plotted in Figure 4, according to C_{80} values of -3 , 0 , and $+3$ dB. It should be noted here that the psychological scales obtained from the experiments performed separately are not comparable.

First, let us compare the two stimuli with the same LE_{late} , that is, stimuli nos. 5 and 7 ($LE_{late} = 0.10$), nos. 2 and 3 ($LE_{late} = 0.25$), and nos. 4 and 6 ($LE_{late} = 0.60$). In

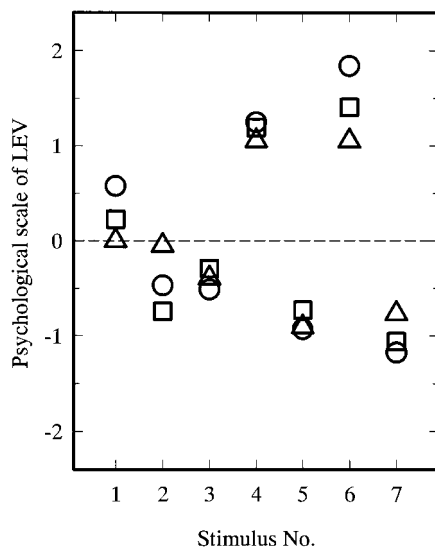


Fig. 4 Psychological scale of LEV in experiment 2. \circ , for C_{80} of -3 dB; \square , for C_{80} of 0 dB; \triangle , for C_{80} of $+3$ dB.

these sets of stimuli, VE_{late} and BE_{late} are reversed in magnitude. The differences in LEV between the two stimuli in each set are not psychologically significant for any C_{80} , because they do not exceed 0.68. This means that the effects of VE_{late} and BE_{late} are not clear. Next, let us compare the two stimuli with the same BE_{late} , that is, stimuli nos. 2 and 4 ($BE_{late} = 0.05$), nos. 6 and 7 ($BE_{late} = 0.20$), and nos. 3 and 5 ($BE_{late} = 0.55$). In these sets of stimuli, the magnitudes of LE_{late} and VE_{late} are reversed. When BE_{late} is 0.05 and 0.20, LEV increases as LE_{late} increases. The differences in LEV between the two stimuli are significantly large (1.10 to 3.01). This suggests that the effect of LE_{late} on LEV is larger than that of VE_{late} . However, there is no noticeable difference of more than 0.68 between stimuli nos. 3 and 5 for any C_{80} . This means that the effects of LE_{late} and VE_{late} are not clear when BE_{late} is higher. In the same way, comparing the two stimuli with the same VE_{late} , that is, stimuli nos. 3 and 6 ($VE_{late} = 0.10$), nos. 4 and 5 ($VE_{late} = 0.25$), and nos. 2 and 7 ($VE_{late} = 0.60$), it is found that the effect of LE_{late} on LEV is larger than that of BE_{late} for VE_{late} values of 0.10 and 0.25, and that their effects are not clear for VE_{late} of 0.60.

Thus, the perception of LEV is complicatedly related to the directional late energy ratios, and it cannot be simplistically explained with only one directional parameter. Therefore, multiple regression analyses were done for three conditions of C_{80} to investigate the degree of contribution of each directional late energy ratio to LEV. The psychological interval scale of LEV was used as a criterion variable, and LE_{late} , VE_{late} , and BE_{late} as explanatory variables. Table 4 shows the results of the multiple regression analyses. A variance test ensured that the results were significant at a level below 1% for a C_{80} of -3 dB and 0.5% for C_{80} values of 0 and $+3$ dB. Since the multiple correlation coefficient is more than 0.989, the accuracy of these analyses is very satisfactory in any test. The standard regression coefficient of LE_{late} is the highest for any C_{80} . The coefficients of VE_{late} are 31 and 48 percents of those of LE_{late} , and the coefficients of BE_{late} are 46 and 49 percents of those of LE_{late} for C_{80} values of -3 and 0 dB,

Table 4 Results of multiple regression analyses between perceived LEV and three directional late energy ratios in experiment 2, significant at $p < 0.01$ for $C_{80} = -3$ dB, $p < 0.005$ for $C_{80} = 0, +3$ dB.

| Experiment no. | C_{80} (dB) | Multiple correlation coefficient | Standard regression coefficients | | |
|----------------|---------------|----------------------------------|----------------------------------|-------------|-------------|
| | | | LE_{late} | VE_{late} | BE_{late} |
| 2(a) | -3 | 0.989 | 1.791 | 0.860 | 0.870 |
| 2(b) | 0 | 0.990 | 1.586 | 0.486 | 0.722 |
| 2(c) | $+3$ | 0.997 | 1.086 | 0.200 | -0.004 |

respectively. They are very low for a C_{80} of +3 dB. This means that the contribution of late sound from above and behind the listener to LEV increases as the late energy increases, and that it reaches about 50 percent as much as the contribution of lateral energy when C_{80} is -3 dB. This tendency agrees with the results of the experiments concerning the effect of reflections from behind the listener on LEV by Morimoto *et al.* [12]. Morimoto suggested that the perception of LEV was related to the law of the first wave front. Namely, the energy of the component of reflections beyond the upper limit of the law, which can contribute to LEV, increases with a decrease in C_{80} , and consequently, the positive effect of back and overhead late energy on LEV seems to be greater.

From these discussions, it can be concluded that not only does the late lateral energy ratio strongly affect LEV, but that late overhead and back energy ratios are definitely effective for LEV at the rate of approximately 30 to 50 percent of the effect of lateral energy ratio when the late energy is larger than the early one.

5. CONCLUSION

In the first experiment, the late sound levels arriving from four fundamental directions are independently varied. The results show that LEV increases with increases in overhead and back sound levels when the late lateral sound level is constant. Namely, it is reconfirmed that not only the late lateral sound level, but also the late sound levels from above and behind the listener significantly affect LEV. Furthermore, it is found that the degrees of contribution of late sound level from above and behind the listener are about 50 percent of that of lateral sound level, and that the degrees of contribution of the directional late sound levels to LEV increase in order of lateral, back, overhead, and frontal. In the second experiment, the directional late energy ratios are varied keeping the total level of late sound constant. The multiple regression analyses indicate that the late lateral energy ratio strongly affects LEV, and that late overhead and back energy ratios are definitely effective for LEV at the rate of approximately 30 to 50 percent of the effect of lateral energy ratio when the late energy is larger than the early one.

The spatial effect of reflections arriving from directions other than lateral, such as back and overhead, has hardly been investigated up to the present, except for a few works. The reason is presumably that they were assumed to have a negative effect on LEV on the basis of binaural interdependence, and not to contribute to the spatial impression at all. From the present results, it is reconfirmed that late sound from directions other than lateral also effectively contributes to the perception of LEV. Therefore, the idea that reflections arriving from directions other than lateral must be always excluded in order to create a sense of

envelopment seems to be very risky in the acoustical design of concert auditoria. A proper directional distribution of late reflections should also be considered in order to realize the feeling of being surrounded by sound images. Further research on the optimum conditions for the directional distribution of late sound is needed.

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REFERENCES

- [1] M. Morimoto and Z. Maekawa, "Auditory spaciousness and envelopment," *Proc. 13th ICA Belgrade*, Vol. 2, pp. 215–218 (1989).
- [2] J. S. Bradley and G. A. Soulodre, "The influence of late arriving energy on spatial impression," *J. Acoust. Soc. Am.*, **97**, 2263–2271 (1995).
- [3] M. Barron and A. H. Marshall, "Spatial impression due to early lateral reflections in concert halls: The derivation of a physical measure," *J. Sound Vib.*, **77**, 211–232 (1981).
- [4] M. Morimoto, S. Sugiura and K. Iida, "Relation between auditory source width in various sound fields and degree of interaural cross-correlation: Confirmation by constant method," *Appl. Acoust.*, **42**, 233–238 (1994).
- [5] J. S. Bradley and G. A. Soulodre, "Objective measures of listener envelopment," *J. Acoust. Soc. Am.*, **98**, 2590–2597 (1995).
- [6] M. Morimoto and K. Iida, "A new physical measure for psychological evaluation of a sound field: Front/back energy ratio as a measure for envelopment," *J. Acoust. Soc. Am.*, **93**, 2282 (1993).
- [7] T. Hanyu and S. Kimura, "A new objective measure for evaluation of listener envelopment focusing on the spatial balance of reflections," *Appl. Acoust.*, **62**, 155–184 (2001).
- [8] H. Furuya, K. Fujimoto, Y. J. Choi and N. Higa, "Arrival direction of late sound and listener envelopment," *Appl. Acoust.*, **62**, 125–136 (2001).
- [9] L. L. Thurstone, "A law of comparative judgment," *Psychol. Rev.*, **35**, 273–286 (1927).
- [10] D. W. Robinson and L. S. Whittle, "The loudness of directional sound fields," *Acustica*, **10**, 74–80 (1960).
- [11] A. Wakuda, H. Furuya, K. Anai and K. Fujimoto, "Directional characteristics of late sounds in concert auditoria," *Proc. Forum Acusticum Sevilla 2002*, RBA-02-014 (2002).
- [12] M. Morimoto, K. Iida and K. Sakagami, "The role of reflections from behind the listener in spatial impression," *Appl. Acoust.*, **62**, 109–124 (2001).



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