CONTRIBUTION OF DIRECTIONAL ENERGY COMPONENTS OF LATE SOUND TO LISTENER ENVELOPMENT

PACS: 43.55.Hy

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ABSTRACT

Two kinds of psychological experiments are conducted to make clear the degree of contribution of directional energy components of late sound to listener envelopment (LEV). In the first experiment, late sound level arriving from four directions; namely, lateral, frontal, overhead, and back, is independently varied. The result shows that not only lateral level but also the late sounds from above and behind the listener affect LEV significantly. In the second experiment, directional late energy ratios are varied keeping a total level of late energy constant. The result indicates the degree of contribution of lateral, overhead, and back late energy to LEV.

INTRODUCTION

Spatial impression is one of the most important psychological factors that aid in the evaluation of the sound field in concert halls. Morimoto [1] and Bradley [2] demonstrated that spatial impression consists of at least two aspects, namely, 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, and the latter is defined as the listener's sensation of the space being filled with sound images other than a sound image composing ASW. Then, some related works have shown that ASW is influenced mainly by early lateral reflections and that LEV is produced predominantly by later 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 [3, 4]. Therefore, the spatial effects in three-dimensional sound fields, in which listeners are exposed to the reflections coming from various directions with a vertical energy component, have not been made clear yet. 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 listener envelopment perceived in a three-dimensional enclosure.

The major concern here originates from a simple question of whether or not listener envelopment, an acoustical sensation of three-dimensional space, is created by lateral sound energy alone, though it is accepted that LEV is strongly related to late-arriving lateral energy. The purpose of this study, therefore, lies basically in investigating the effects of the directional energy components of late sound on LEV, and clarifying an objective measure for the prediction of LEV by taking every factor into consideration. In our previous work [5], it was shown that the late sound level from above and behind the listener correlated with LEV positively and strongly as well as from lateral direction, and that not only late lateral sound but also late sound from directions other than lateral contributes to the perception of LEV.

In this paper, two kinds of psychological experiments are conducted with simulated sound fields to reconfirm the effect of late sound from directions other than lateral on LEV, and to make clear the degree of contribution of directional energy components to LEV. Firstly, in experiment 1, the effects of level changes in late sound arriving from four directions, namely, lateral, frontal, overhead, and back, on perceived LEV are investigated. Secondly, in experiment 2, the effects of the directional late energy fractions on LEV are investigated to clear the degree of contribution of the directional late energy using sound fields with a constant level of total late energy.

METHOD

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 and two loudspeakers for early reflections were placed symmetrically at azimuth angles of ± 45° 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 to five loudspeakers. Four of them were located at azimuth angles of ± 90° (left and right), 0° (front), and 180° (back) on the horizontal plane. 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.

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. Before the experiments, the term 'listener envelopment' was explained to them with a conceptual illustration and some comments, which expressed the definition of LEV mentioned above. A preliminary practice session was held in order to ensure that the subjects were familiar with the requirements of each test. Each subject, who was seated with his/her head fixed, was individually required to judge the difference in perceived LEV between each pair of sound fields. Namely, the subject judged whether LEV for the second stimulus was weaker or stronger than that for the preceding one in a pair of sound fields.

Psychological Analysis In both experiments, psychological interval scales of LEV were constructed from experimental results by the method of Thurstone's Case V [6]. This method is one of the approximations for solving an equation of 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 a probability of judgment for $S_i > S_j$ is equal to 75 %.

Physical Parameters Four directional late sound levels and four directional late energy ratios were calculated from the overall impulse responses obtained using 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 level of each directional late energy to a 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 total energy of late sound. The listening sound pressure level was measured using a dummy head microphone for the music source. The A-weighted binaural *SPL* [7] (*BSPL*) was calculated by the equation to obtain a binaural summation of the loudness of the sound fields, using the measured levels (the time constant: slow) at the left and the right ears of dummy head.

EXPERIMENT 1

The object of the first experiment is 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.

<u>Experimental Conditions</u> The structure of the sound fields is diagrammatically shown in Figure 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* was 0.17. The reverberation time was set at 1.8 s. As given in Table 1, seven kinds of sound fields were used in experiment 1. In stimulus no. 1, 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 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 almost kept constant. Therefore, the late lateral level was almost equal in 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, 21 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.

<u>Results And Discussion</u> 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 result of the conformity-test with Thurstone's 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 difference in LEV is discussed on the basis of jnd of LEV.

First, let us consider the effect of the change of late lateral sound level. Figure 3(a) shows that LEV clearly becomes stronger with the increase of LL_{late}. Namely, the maximum difference in LEV between stimuli nos. 1 to 3 is 3.21, corresponding to 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, except stimulus no. 6, exceed 0.68. In other words, the subjective changes in LEV are distinctly perceived in 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 late sound level from directions other than lateral. Figures 3(c) and (d) show that LEV becomes stronger with the increase of VL_{late} and BL_{late}. The difference in LEV between stimuli nos. 1 and 5 is 1.77, corresponding to change of 8 dB in VL_{late}. The difference in LEV between stimuli nos. 1 and 7 is 2.52, corresponding to 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 Figure 3(b), the difference in LEV between stimuli nos. 1 and 6 (0.63) is not psychologically significant, corresponding to change of 8 dB in FL_{late}.

Furthermore, the multiple regression analysis was done to investigate the degree of contribution of each directional late level to perceived LEV. The psychological interval scale of LEV was used as a criterion variable and the four directional late levels 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 result was 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}. The coefficients for VL_{late} and BL_{late} are somewhat lower than that for LL_{late}, but the result indicates that they also affect the perceived LEV.

From these discussions, it can be concluded that not only the late lateral sound level but also the late sound levels from directions other than lateral contribute to LEV. Namely, late lateral sound has the largest effect on LEV, while late sound arriving from above and behind the listener also significantly affects the perceived LEV. Furthermore, the degree of contribution of directional late sound levels to LEV increases in order of lateral, back, overhead, and frontal. These results coincide with the findings in our previous work [5].

EXPERIMENT 2

In the preceding experiment, the total level of late sound was not constant, because only 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.

Experimental Conditions As shown in Figure 2, the structure of impulse responses and the conditions of direct sound and early reflections were quite the same as 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 through the tests. Experiment 2 consisted of three separate tests, experiments 2(a), (b), and (c), according to the 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 the three steps over a range from 0.05 to 0.60, referring to the measured values in auditoria [8]. All combinations of seven stimuli, namely 21 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.

Results And Discussion The result of the conformity-test with Thurstone's Case V model showed that the experimental data was significant at a level below 1 %. The psychological interval scales of LEV are plotted in Figure 4, according to C_{80} of −3, 0, and +3 dB. Here, it should be noted 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 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 VE_{late} and BE_{late} are almost equivalent in the effect on LEV. 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 indicates that LE_{late} contributes to LEV. However, there is no noticeable difference more than 0.68 between stimuli nos. 3 and 5 for any C_{80}. This means that the changes of LE_{late} and VE_{late} do not affect LEV 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 effects of LE_{late} and BE_{late} on LEV are not recognized when VE_{late} is higher.

Thus, the perception of LEV is complicatedly related to the directional late energy ratios, and it cannot be simplistically explained with one directional parameter alone. Therefore, the 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 multiple regression analyses. A variance test ensured that the results were significant at a level below 1 % for C_{80} of –3 dB, and 0.5 % for C_{80} 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} and BE_{late}

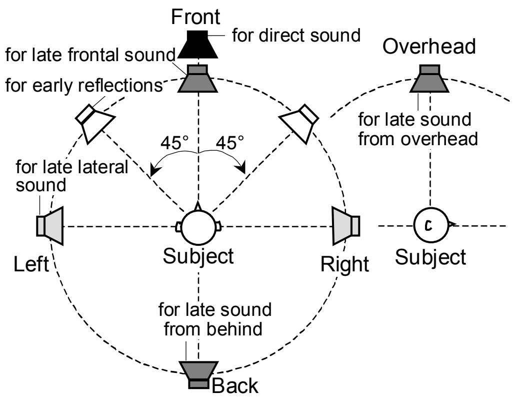

Fig. 1. Arrangement of loudspeakers in an anechoic chamber.

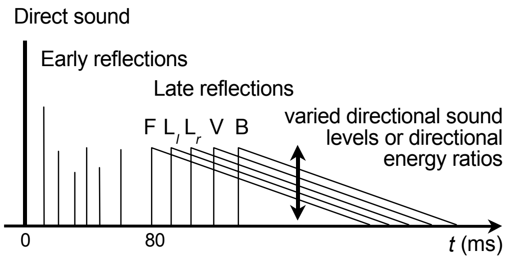

Fig. 2. Structure of the sound fields used in the experiments (F=frontal, L=lateral, V=overhead, and B=behind; subscripts *l* and *r*: left and right). In experiment 1, each directional late level is independently varied. In experiment 2, directional late energy ratios are varied keeping the total level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

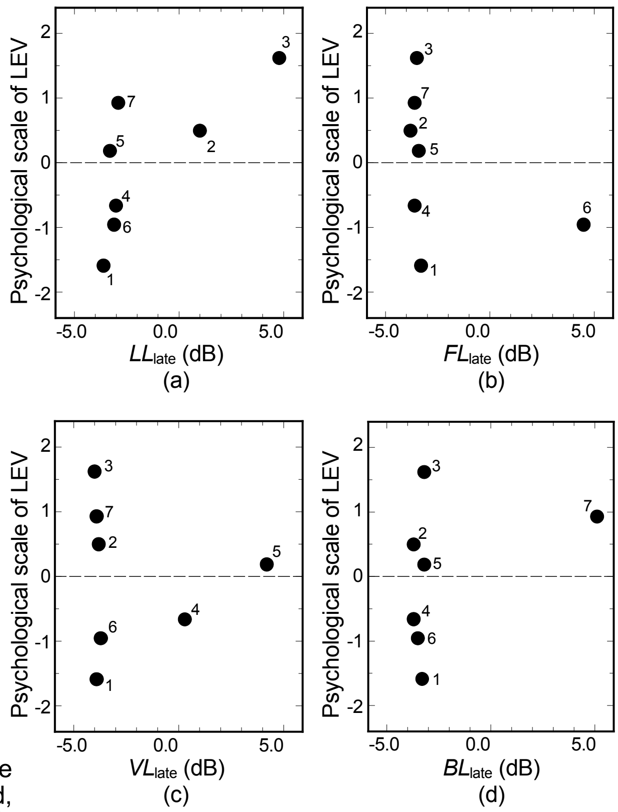

Fig. 3. Psychological scale of LEV versus four directional late levels in experiment 1. The subscript indicates the stimulus no.

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**

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

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		0.30	0.30	0.30	0.10
2			0.60	0.05	0.10
3			0.10	0.55	0.10
4	63	0.60	0.25	0.05	0.10
5		0.10		0.55	0.10
6		0.60	0.10		0.10
7		0.10	0.60		0.10

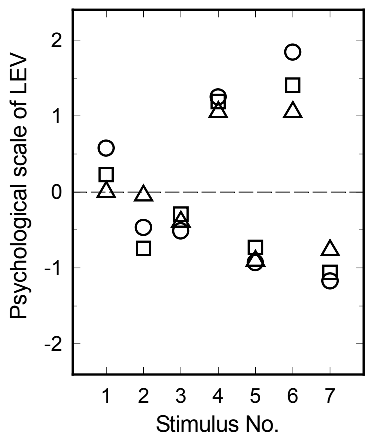

Fig. 4. Psychological scale of LEV in experiment 2. ○, for C_{80} of –3 dB; □, for C_{80} of 0 dB; △, for C_{80} of +3 dB.

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

are approximately 30 to 50 percent of those of LE_{late} for C_{80} of –3 and 0 dB, while they are very low for 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 result of experiments concerning the effect of reflections from behind the listener on LEV by Morimoto [9]. 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 of 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 late lateral energy ratio affect LEV strongly, but that late overhead and back energy ratios contribute to LEV definitely, according to the ratio of early-to-late sound energy.

CONCLUSIONS

In the first experiment, late sound level arriving from four fundamental directions is independently varied. The result shows that LEV increases with the increase of overhead and back sound level when late lateral sound level is constant. That is, not only late lateral sound level but also the late sound level from above and behind the listener affects LEV significantly. Furthermore, it is found that the degree of contribution of directional late sound level to LEV increases in order of lateral, back, overhead, and frontal. In the second experiment, three directional late energy ratios are varied keeping a total level of late sound. The multiple regression analyses indicate that late lateral energy ratio strongly affects LEV, and late overhead and back energy ratios also contribute to LEV, according to the ratio of early-to-late sound energy.

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 was presumably that they were assumed to have a negative effect on LEV on the basis of binaural interdependence, and not to contribute to spatial impression at all. From the present results, it is reconfirmed that late sounds from directions other than lateral also contribute to the perception of LEV definitely. Therefore, the idea that reflections arriving from directions other than lateral must be excluded for creating a sense of envelopment seems to be very risky in acoustical design of concert auditoria. A well-balanced directional distribution of late reflections should also be considered in the sense of feeling surrounded by sound images. Further research on the optimum conditions for the directional distribution of late sound is needed.

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