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Relation between Listener Envelopment and Late Arriving Energy in Concert Auditoria

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ABSTRACT

In concert hall acoustics, spatial perception is one of the most important psychological factors that aid in the evaluation of the sound field. This paper discusses the relation between subjective listener envelopment (LEV) and directional characteristics of late-arriving sound through a series of psycho-acoustical experiments. The purposes of four experiments are: (1) to investigate the individual effect of late energy arriving from four fundamental directions, namely, lateral, frontal, back, and overhead, on LEV, using simulated sound fields in which the late sounds, except for a varied directional sound, are kept constant, (2) to investigate the effect of directional late energy ratios (DLR) on LEV when the late-to-early sound ratio TL is constant, using sound fields in which all of the late sound have a single directional energy component, (3) to investigate whether or not the effect of late energy with a single directional component is applicable to the realistic case when late sounds have plural directional components, using sound fields with late sounds arriving from arbitrary directions, and (4) to clarify the degree of contribution of the directional property and total energy of late sound to LEV, using sound fields in which both DLR and TL are varied.

KEYWORDS: Concert hall acoustics, Listener envelopment, Directional late sound

INTRODUCTION

The major concern of this study 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 [1]. In acoustic design of actual auditoria, the architectural conditions for securing the lateral reflections enough to produce the desired LEV are not necessarily satisfactory because of some restrictions on architectural planning, etc. Suppose that late sounds from directions other than lateral, such as from above and

behind the listener, are also effective in the perception of LEV to a greater or lesser degree, the incorporation of non-lateral late sounds into a policy of acoustic design enables us to compensate for lack of LEV in the situation mentioned above. In other words, if the degrees of contribution of not only lateral but other directional late sound to LEV are cleared, we can have more options and possibilities in design method for LEV than in the method only with lateral reflections. The basic goal of this study, therefore, is to clarify the relation between the directional energy components of late sound and perceived LEV so that it can be utilized for controlling LEV in a design stage. In this paper, the results of four psycho-acoustical experiments are introduced.

METHOD OF SUBJECTIVE EXPERIMENTS

A series of subjective experiments was conducted using simulated sound fields in an anechoic chamber. The sound fields consisted of a direct sound, six discrete early reflections derived from multi-tap delay machines, and later sound added by digital reverberators. In all tests, a loudspeaker for direct sound and two loudspeakers for early reflections were fixed, and the delay times and the levels of early reflections relative to the direct sound were kept constant so that LF_{80} was 0.17. Late sound arriving more than 80 ms after the direct sound was fed to five or six loudspeakers. All the loudspeakers were equidistant (1.5 m) from the listener. The reverberation time was set at 1.8 s.

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. All the sound field pairs, followed by an interval of 5 s, were presented to the subjects in random order. The subjects were students, 20 to 26 years old, with normal hearing sensitivity. Before the experiments, the term 'listener envelopment' was explained to them using a conceptual illustration and some comments which expressed the 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 was individually required to judge whether the LEV for the second stimulus was weaker or stronger than that for the preceding one in a pair of sound fields.

Psychological interval scales of LEV were constructed from the experimental results by the method in Thurstone's Case V [2]. A psychological interval between two stimuli, S_i and S_j , corresponding to just noticeable difference, subjective- jnd , is approximately 0.68 on this scale, the value of which is calculated when the probability of judgment for $S_i > S_j$ is equal to 75 %.

Four directional late sound levels and four directional late energy ratios (DLR) were calculated from the overall impulse responses obtained with omni-directional and figure-of-eight microphones in order to determine the directional distribution of late 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. In Experiments 2, 3, and 4, 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 late energy. The late-to-early sound ratio TL was defined as the reciprocal of C_{80} . The A-weighted binaural SPL [3], $BSPL$, was measured as an indicator of loudness, using a dummy head microphone for the music source.

EXPERIMENT 1: EFFECT OF LATE SOUND FROM LATERAL AND OTHER DIRECTIONS ON LEV

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

Experimental Conditions

Figure 1 shows the arrangement of the loudspeakers in Experiment 1. Five loudspeakers for late sounds (left, right, frontal, back, and overhead) were located around the listener. Figure 2 illustrates the structure of the sound fields.

Experiment 1 consisted of four tests, namely, Experiments 1(a), 1(b), 1(c), and 1(d), according to the four arrival directions of the late sound. As given in Table 1, each test was independently performed using four sound fields, including a common field (stimulus no. 1). The late sound was radiated from all loudspeakers in all tests. In Experiment 1(a), only the late lateral sound level was varied in the four steps over a range of approximately 9 dB, which is a little smaller than the range generally obtained in real auditoria. Similarly, only the late frontal sound level was varied in Experiment 1(b), only the late overhead sound level was varied in Experiment 1(c), and only the late back sound level was varied in Experiment 1(d). The late energy, except for the varied directional sound, was kept constant in each experiment. Consequently, the late-to-early sound ratio TL was in the range of -3 to 2 dB.

In each test, all combinations of the four stimuli, six pairs, were presented to eight subjects. Each subject individually judged each pair of sound fields eight times, and thus, a total of 48 judgements was made for each test. The $BSPLs$ with the music source were in the range of 63 to 67 dB in Experiment 1(a), 63 to 65 dB in Experiment 1(b), and 63 to 64 dB in Experiments 1(c) and (d).

Results and Discussion

The results of the conformity-tests with Thurstone's Case V model showed that the experimental data was significant at a level below 1 %. The standard of judgment was agreed upon by all subjects at a level below 5 % of significance, which was the same in all the following experiments. The psychological interval scales of LEV versus directional late sound levels LL_{late} , FL_{late} , VL_{late} , and BL_{late} are plotted in Figures 3(a), (b), (c), and (d), respectively. It is found that LEV is positively correlated with each directional sound level, except for FL_{late} . The late lateral sound level LL_{late} correlates most strongly with LEV, as is generally accepted. In addition, the correlation coefficients between LEV and the values of VL_{late} and BL_{late} exceed 0.98. Namely, LEV clearly becomes stronger with increases in them. This means that LEV is dependent on late sound not only from a lateral direction, but also from above and behind the listener. Only the late frontal sound level does not correlate with LEV at all.

The maximum differences in scale values relative to stimulus no. 1 are 3.38, 2.92, and 1.98, respectively, corresponding to changes of 9 dB in LL_{late} , 7 dB in VL_{late} , and 11 dB in BL_{late} . These differences are significantly large. In other words, the changes in LEV are well discriminated according to a level variation in late sound from lateral, overhead, and rear directions. As for the late frontal sound, the difference in LEV between $FL_{late}=1.3$ and 3.7 dB is more than the subjective- jnd of 0.68. Therefore, although the late frontal sound does not correlate with LEV, it cannot be considered under this experimental condition that it does not contribute to LEV.

Furthermore, it should be noted that the ranges of change in $BSPL$ were 4 dB in Experiment 1(a), 2 dB in Experiment 1(b), and only 1 dB in Experiments 1(c) and (d). That is, the difference in LEV for changes in LL_{late} includes the large effect of the 4-dB increase in loudness, while the difference in LEV for changes in VL_{late} and BL_{late} barely include the effect.

From these discussions, it can be concluded that not only the late lateral sound but also the late sounds coming from above and behind the listener correlate with LEV positively.

EFFECT OF DIRECTIONAL LATE ENERGY RATIO ON LEV

In the preceding experiment the total late energy was not constant, because only a directional late sound level was independently varied keeping others constant. In Experiments 2 and 3, the relation between the directional late energy ratio and LEV is investigated keeping the late-to-early sound ratio TL constant.

Experiment 2: Effect of Late Sound with a Single Directional Energy Component

Experimental Conditions. As shown in Figures 1 and 2, the structure of impulse responses was quite similar to that used in Experiment 1. The directional late energy ratios, LE_{late} , VE_{late} , and BE_{late} , were varied keeping the TL 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 values of TL which were set at +3, 0, and -3 dB. As given in Table 2, 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 [4]. 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, and thus, a total of 168 judgments were made. The $BSPL$ was constant at 63 dB.

Results and Discussion. The results of conformity-tests with the Thurstone's 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 TL 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. As mentioned above, the significance of the difference in LEV is discussed on the basis of the subjective- jnd of LEV.

First, let us compare the two stimuli with the same LE_{late} , that is, stimuli nos.5 and 7 (0.10), nos.2 and 3 (0.25), and nos.4 and 6 (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 TL , 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 (0.05), nos.6 and 7 (0.20), and nos.3 and 5 (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 TL . 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 (0.10), nos.4 and 5 (0.25), and nos.2 and 7 (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 explained only with one directional parameter, because the three DLRs were varied simultaneously in each sound field. Therefore, multiple regression analyses were done for three conditions of TL to investigate the degree of contribution of each DLR 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 3 shows the standard regression coefficients, which express the contribution of the DLRs to LEV. A variance test ensured that the results were significant at a level below 1 % for a TL of +3 dB and 0.5 % for TL 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 TL . 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 TL values of 0 and +3 dB, respectively. They are very low for a TL of -3 dB. This means that the contribution of VE_{late} and BE_{late} to LEV increases as the total late energy increases. In addition, this tendency agrees with the results of the experiments concerning the effect of reflections from behind the listener on LEV by Morimoto *et al.* [5]. Morimoto suggested that the perception of LEV was related to the law of the first wave front. Namely, the energy component of reflections beyond the upper limit of the law, which can contribute to LEV, increases with an increase in TL , and consequently, the positive effect of back and overhead late energy on LEV presumably becomes greater.

From these discussions, it can be concluded that not only does the late lateral energy ratio

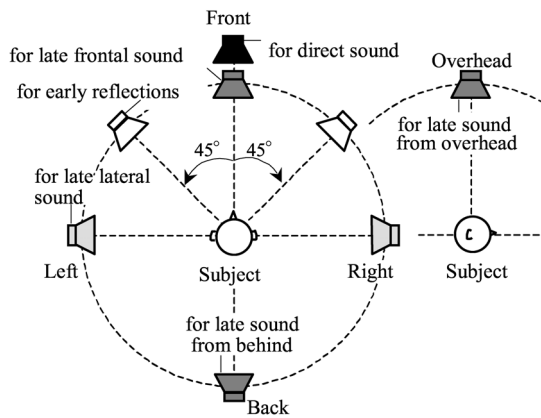


Figure 1 Arrangement of loudspeakers in Experiments 1, 2, and 4.

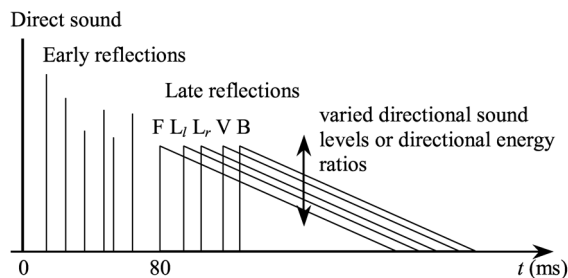


Figure 2 Structure of the sound fields used in Experiments 1, 2, and 4. (F=frontal, L=lateral, V=overhead, and B=behind; subscripts l and r: left and right) In Experiment 1, each directional late sound level is independently varied. In Experiment 2, directional late energy ratios are varied keeping the total late energy constant. In Experiment 4, late-to-early sound ratio is additionally varied.

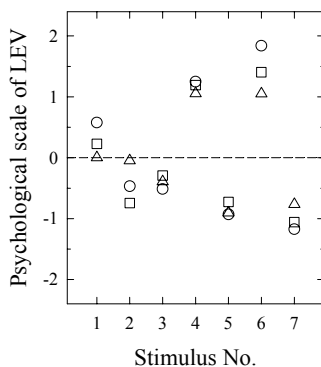


Figure 4 Psychological scale of LEV in Experiment 2: open circle, for TL of +3 dB; square, for TL of 0 dB; triangle, for TL of -3 dB.

Table 1 Thirteen sound fields used in Experiment 1.

Experiment no.	Stimulus no.	TL (dB)	Directional late sound levels (dB)			
			LL _{late}	FL _{late}	VL _{late}	BL _{late}
Common field*	1	-3	-3.5	-6.3	-3.6	-6.3
	2	-2	-0.7	-6.7	-3.7	-6.7
	3	0	3.3	-6.3	-3.4	-6.3
	4	2	5.1	-5.9	-3.3	-5.9
	5	-1	-3.5	-1.0	-3.5	-6.3
	6	0	-3.2	1.3	-3.3	-6.3
	7	2	-3.5	3.7	-2.8	-6.3
	8	-2	-3.5	-6.7	-1.5	-6.7
	9	0	-3.4	-6.0	1.1	-6.0
	10	2	-3.2	-6.3	3.8	-6.3
	11	-1	-3.8	-6.3	-3.6	-0.1
	12	0	-3.1	-6.3	-3.3	2.1
	13	2	-3.4	-6.3	-3.2	4.4

* Stimulus no.1 is included in all tests.

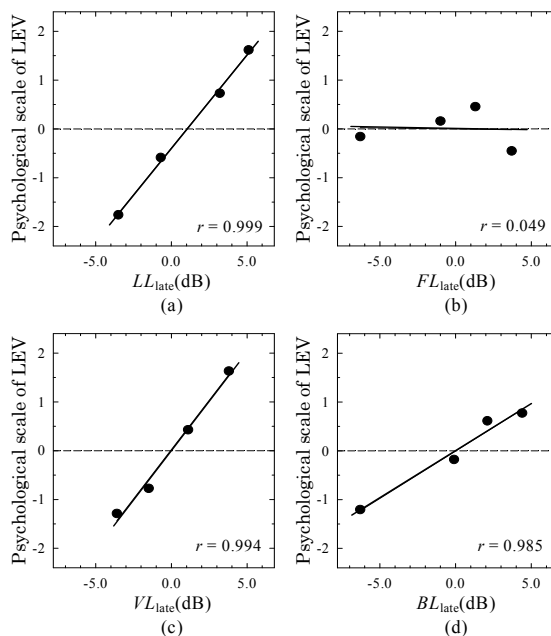


Figure 3 Psychological scale of LEV in Experiment 1, r: correlation coefficient.

Table 2 Seven sound fields used in Experiment 2.

Stimulus no.	BSPL (dB)	Directional late 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

Table 3 Results of multiple regression analyses between LEV and three directional late energy ratios in Experiment 2, significant at $p < 0.01$ for TL of +3 dB, $p < 0.005$ for TL of 0 and -3 dB.

Experiment no.	TL (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

strongly affect LEV, but that late overhead and back energy ratios are definitely effective for LEV in around fifty percent of the effect of lateral energy ratio when the late energy is not smaller than the early one.

Experiment 3: Effect of Late Sound with Plural Directional Energy Components

Experiment 2 was based on tests in simulated sound fields in which all of the late energy had a single directional component in order to examine directly the effect of three fundamental directional energy components (lateral, longitudinal, and vertical). In this experiment, the effect of DLR on LEV was examined using sound fields with late sounds arriving from arbitrary directions to clarify whether or not the contribution of late energy with a single directional component, the result of Experiment 2, is applicable to the realistic case when the late sound has plural directional energy components.

Experimental Conditions. Figure 5 shows the arrangement of the loudspeakers in Experiment 3. Six loudspeakers were located for late sounds. The late sounds except from behind the listener (L6) consist of plural directional energy components. The structure of the sound fields is shown in Figure 6. The experiment consisted of two separate tests, according to the values of TL which were set at +3 and 0 dB. The LE_{late} , VE_{late} , and BE_{late} were varied keeping the TL constant in the same way as Experiment 2. As given in Table 4, seven kinds of sound fields were used in each test. All combinations of seven stimuli, twenty-one pairs, were presented to seven subjects. Each subject judged each pair of stimuli eight times.

Results and Discussion. The results of conformity-tests with the Thurstone's Case V model showed that the experimental data was significant at a level below 1 %. The psychological interval scales for LEV were obtained from the results, according to TL values of +3 and 0 dB. In the same manner as Experiment 2, however, the relation between the DLRs and perceived LEV cannot be interpreted only with one directional parameter. From the results of multiple regression analyses, the relative ratio of the standard regression coefficients of VE_{late} and BE_{late} to that of LE_{late} shows a similar tendency with the results in the preceding Experiment 2, in which all of the late sounds have a single directional energy component. Figure 7 shows the comparison between measured LEV in Experiment 3 and calculated LEV by using the regression equations that have been obtained from the result in Experiment 2. They give a good agreement, because the correlation coefficients between them are about 0.93 or more for any TL .

From these discussions, it can be concluded that the preceding findings about the contribution of late energy with a single directional component to LEV are valid when the late sounds have plural directional components.

EXPERIMENT 4: CONTRIBUTION OF DIRECTIONAL LATE ENERGY RATIO AND LATE-TO-EARLY SOUND RATIO TO LEV

In Experiment 4, the effects of directional distribution and total energy of late sound on perceived LEV are investigated, using the sound fields in which both DLR and TL are simultaneously varied.

Experimental Conditions

The arrangement of the loudspeakers and the structure of the sound fields are shown in Figures 1 and 2, respectively. The TL value was varied over a range of -5 to $+5$ dB corresponding to different levels of the total late energy, and the four DLRs were randomly varied from 0.05 to 0.81 in each stimulus. Thus, there were twenty different sound fields, as given in Table 5. All combinations of twenty stimuli, namely, one hundred and ninety pairs, were presented to fourteen subjects. Each subject was tested individually to judge each pair of stimuli four times, and thus, a total of 760 judgments were made.

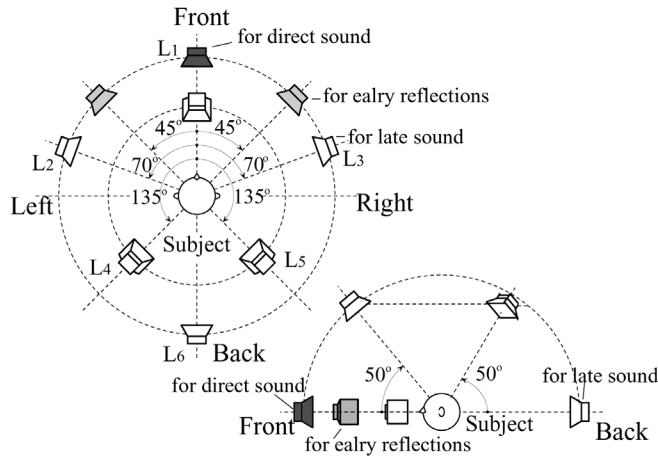


Figure 5 Arrangement of loudspeakers in Experiment 3.

Table 4 Seven sound fields used in Experiment 3.

Stimulus no.	BSPL (dB)	Directional late energy ratios			
		LE_{late}	VE_{late}	BE_{late}	FE_{late}
1		0.30	0.30	0.30	0.10
2		0.20	0.50	0.20	0.10
3		0.30	0.10	0.50	0.10
4	63	0.50	0.25	0.15	0.10
5		0.10	0.25	0.55	0.10
6		0.60	0.10	0.20	0.10
7		0.20	0.55	0.15	0.10

Table 5 Twenty sound fields used in Experiment 4.

Stimulus no.	BSPL (dB)	TL (dB)	Directional late energy ratios			
			LE_{late}	VE_{late}	BE_{late}	FE_{late}
1		5	0.10	0.59	0.10	0.18
2		5	0.19	0.41	0.23	0.15
3		4	0.43	0.08	0.29	0.10
4		3	0.10	0.81	0.05	0.05
5		3	0.09	0.21	0.59	0.10
6		2	0.31	0.10	0.51	0.05
7		2	0.44	0.39	0.15	0.05
8		1	0.22	0.10	0.05	0.65
9		1	0.10	0.10	0.72	0.05
10	63	0	0.32	0.19	0.10	0.41
11		0	0.18	0.69	0.05	0.05
12		-1	0.09	0.32	0.21	0.41
13		-1	0.65	0.29	0.05	0.05
14		-2	0.26	0.29	0.28	0.09
15		-2	0.20	0.55	0.15	0.05
16		-3	0.17	0.16	0.55	0.05
17		-3	0.15	0.54	0.09	0.20
18		-4	0.10	0.42	0.40	0.11
19		-5	0.60	0.20	0.11	0.10
20		-5	0.76	0.11	0.06	0.06

Table 6 The result of multiple regression analysis between LEV and TL and three directional late energy ratios in Experiment 4, significant at $p < 0.005$.

Multiple correlation coefficient	Standard regression coefficients			
	TL	LE_{late}	VE_{late}	BE_{late}
0.932	0.967	0.630	0.223	0.393

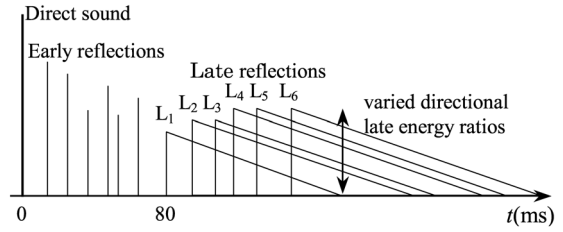


Figure 6 Structure of the sound fields used in Experiment 3. Late sound consists of plural directional energy components.

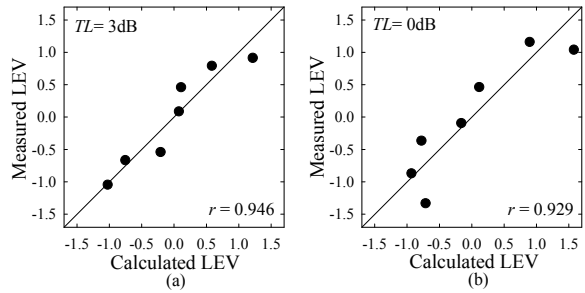


Figure 7 Comparison between measured LEV in Experiment 3 and calculated LEV by the regression equation obtained in Experiment 2, r : correlation coefficient.

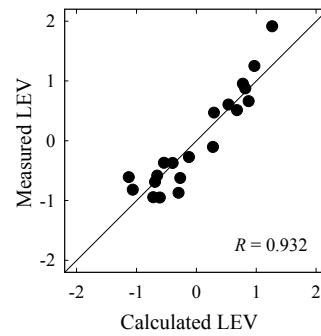


Figure 8 Comparison between measured LEV and calculated LEV in Experiment 4, R : multiple correlation coefficient.

Table 7 Correlations of calculated LEV by the regression equation obtained in Experiment 4 with measured LEV in Experiments 2 and 3.

Exp. no.	Experiment 2			Experiment 3	
	(a)	(b)	(c)	(a)	(b)
TL (dB)	3	0	-3	3	0
r	0.956	0.946	0.610	0.974	0.934

Results and Discussion

The results of conformity-tests with the Thurstone's Case V model showed that the experimental data was significant at a level below 5 %.

In the same way as the preceding experiments, multiple regression analysis was done to clarify the degree of contribution of DLRs and TL to perceived LEV. The psychological interval scale of LEV was used as a criterion variable, and TL , LE_{late} , VE_{late} , and BE_{late} as explanatory variables. Table 6 shows the standard regression coefficients that express the contribution of four physical parameters to LEV. A variance test ensured that the result was significant at a level below 0.5 %. Since the multiple correlation coefficient is 0.932 as shown in Figure 8, the accuracy of this analysis is very satisfactory. The value of standard regression coefficient is the highest for TL . Namely, this means that the contribution of the total late energy to LEV is large. Regarding the contribution of DLRs, the coefficient of LE_{late} is the highest among them, and the coefficients of VE_{late} and BE_{late} are 35 and 62 percents of that of LE_{late} , respectively.

Furthermore, in order to confirm the validity of the result, the measured LEVs in Experiments 2 and 3 were correlated with the calculated LEVs by this regression equation. The correlation coefficients are given in Table 7. Good correlations are obtained, especially for TL values of +3 and 0 dB, namely when the late energy is not smaller than the early one.

From these discussions, it is found that the ratio of late energy to early one has an important effect on perceived LEV. Regarding directional late energy ratios, it is reconfirmed that LE_{late} strongly affects LEV, and VE_{late} and BE_{late} are also effective for LEV in approximately forty and sixty percents of the effect of LE_{late} , respectively.

CONCLUSIONS

Four psycho-acoustical experiments were conducted, and the relation between subjective listener envelopment and directional characteristics of late sound was discussed. The results showed that: (1) Not only the late lateral sound, but also the late sounds arriving from above and behind the listener correlate with LEV positively. (2) The degrees of contribution of the late overhead and back energy ratios to LEV are smaller than that of lateral energy ratio, but they are definitely effective in the perception of LEV, especially when the late energy is not smaller than the early one. (3) The late-to-early sound ratio plays an important role in the perception of LEV. Namely, the intensity of the total late energy has an influence on the degree of contribution of DLR to LEV because of the effect of energy component beyond the upper limit of the law of the first wave front. These results suggest that the directional property of late sound is a considerable aspect for the control of LEV in concert halls.

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