Contribution of Total Energy and Directional Components of Late Sound to Listener Envelopment

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Abstract

The purpose of this study is to clarify the effect of late arriving sound on listener envelopment (LEV). In our previous works, it was shown that late sounds from above and behind the listener as well as lateral, which had a single directional component, significantly affected LEV when the early-to-late sound ratio C_{80} was constant. In this paper, two kinds of psychological experiments are performed with simulated sound fields in order to examine the relation between total late energy and directional late energy ratios DLR, and perceived LEV. In the first experiment, the effect of the total level and the spatial distribution of late sound energy on perceived LEV were examined when both C_{80} and DLR were varied. In the second experiment, the effect of DLR on LEV were 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 is applicable to the realistic case when late sounds have plural directional components.

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 mainly influenced by early lateral reflections, and the latter is predominantly produced by late-arriving lateral reflections.

The major concern of our study originated from the question of whether or not LEV was created by lateral sound energy alone, although it was accepted that LEV was strongly related to late-arriving lateral energy. In our previous works [3] [4], it was shown that late sound from directions other than lateral, namely from back and overhead, also effectively contributes to the perception of LEV especially when the late energy is larger than the early one. However, in order to examine directly the effect of three fundamental directional energy components (lateral, longitudinal and vertical), these previous experiments on LEV were based on tests in simulated sound fields in which all of the late energy had a single directional component and the total late energy was constant.

As the next step, therefore, we need to investigate the effect of not only the directional distribution but also the total energy of late sounds on perceived LEV, and to clear the contribution of late sound energy that consists of plural directional components to LEV. In this paper, two kinds of psychological experiments are conducted in order to clarify the degree of contribution of total energy and directional energy components of late sound to LEV. Firstly, in Experiment 1, the effects of the total energy and the directional distribution of late sound on perceived LEV are investigated when both the early-to-late sound ratio C_{80} and the directional late energy ratios DLR are varied. Secondly, in Experiment 2, the degree of contribution of DLR to LEV is investigated using the late sounds which arrive from arbitrary directions in three-dimensional simulated sound fields.

2. Method

2.1. Procedure

Sound fields were simulated using an electro-acoustic system in 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. All the loudspeakers were equidistant (1.5 m) from the listener. In all tests, the delay times and the levels of early reflections relative to direct sound were kept constant so that LF_{80} was 0.17, and the average reverberation time was set at 1.8 s over the seven octave bands from 125 to 8k Hz.

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' was used as the music motif. All the sound field pairs 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, 20 to 25 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 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 con-

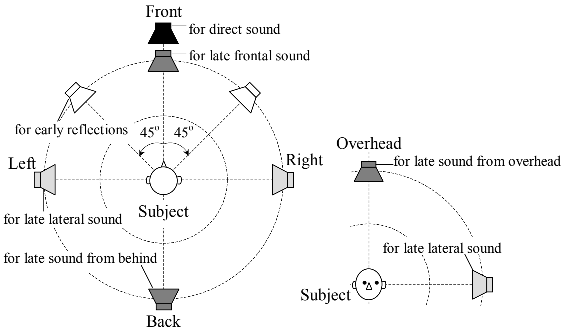

Figure 1: *Arrangement of loudspeakers in Experiment 1.*

structed from the experimental results by the method in Thurstone's Case V [5]. 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 can be calculated when the probability of judgment for $S_i > S_j$ is equal to 75%.

2.2. Physical parameters

Four DLRs were calculated from the overall impulse responses obtained with omni-directional and figure-of-eight microphones in order to determine the spatial distribution of the late-arriving sound energy. 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 A-weighted binaural SPL [6] ($BSPL$), the listening sound pressure level, was measured using a dummy-head microphone for the music source. The $BSPL$ was constant at 63 dB in all tests.

3. Experiment 1

The object of the first experiment was to investigate the effect of the total level and the spatial distribution of late sound energy on perceived LEV, using sound fields in which both C_{80} and DLR were varied.

3.1. Experimental conditions

Figure 1 shows the arrangement of the loudspeakers in Experiment 1. A loudspeaker for direct sound, two loudspeakers for early reflections and five loudspeakers for late sounds (left, right, frontal, back and overhead) were located around the listener.

The structure of the sound fields is diagrammatically shown in Fig. 2. The C_{80} value was varied in twenty steps over a range of -5 to +5 dB corresponding to different levels of the total late energy, and the four DLRs were varied from 0.05 to 0.81, respectively. Thus there were twenty different sound fields, as given in Table 1.

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.

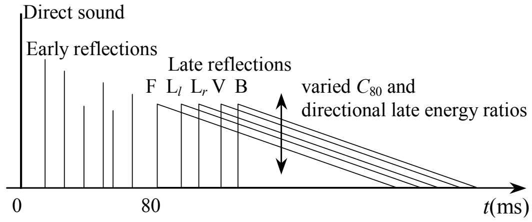

Figure 2: *Structure of the sound fields used in Experiment 1 (F=frontal, L=lateral, V=overhead and B=behind; subscripts l and r : left and right).*

Table 1: *Twenty sound fields used in Experiment 1.*

Stimulus No.	*BSPL* (dB)	C_{80} (dB)	Directional late sound energy ratio			
			LE_{late}	VE_{late}	BE_{late}	FE_{late}
1		-4.9	0.10	0.59	0.10	0.18
2		-4.5	0.19	0.41	0.23	0.15
3		-4.1	0.43	0.08	0.29	0.10
4		-3.4	0.10	0.81	0.05	0.05
5		-2.9	0.09	0.21	0.59	0.10
6		-2.4	0.31	0.10	0.51	0.05
7		-1.9	0.44	0.39	0.15	0.05
8		-1.2	0.22	0.10	0.05	0.65
9		-0.9	0.10	0.10	0.72	0.05
10	63	-0.3	0.32	0.19	0.10	0.41
11		0.3	0.18	0.69	0.05	0.05
12		0.8	0.09	0.32	0.21	0.41
13		1.2	0.65	0.29	0.05	0.05
14		1.5	0.26	0.29	0.28	0.09
15		2.3	0.20	0.55	0.15	0.05
16		2.6	0.17	0.16	0.55	0.05
17		3.1	0.15	0.54	0.09	0.20
18		3.7	0.10	0.42	0.40	0.11
19		4.5	0.60	0.20	0.11	0.10
20		5.0	0.76	0.11	0.06	0.06

3.2. Results and discussions

The results of conformity tests with the Thurstone Case V model showed that the experimental data was significant at a level below 5%. The standard of judgment was agreed upon by all subjects at a level below 5% of significance. The psychological interval scales of LEV versus C_{80}, LE_{late}, VE_{late} and BE_{late} are plotted in Fig. 3(a)-(d), respectively.

Fig. 3(a) shows that there seems to be a low negative correlation between C_{80} and LEV. In other words, LEV becomes stronger with an increase of the ratio of late sound energy to early one. The maximum difference in LEV among twenty stimuli is about 3, corresponding to a change of 10 dB in C_{80}. However, the relation between the DLRs and perceived LEV is not clear only from these results, because five quantities, C_{80} and four DLRs, were varied simultaneously in each sound field.

Therefore, a multiple regression analysis was done to clear the degree of contribution of C_{80} and three DLRs (lateral, overhead and back) to the perceived LEV. The psychological interval scale of LEV was used as a criterion variable, and C_{80}, LE_{late}, VE_{late} and BE_{late} as explanatory variables. Table 2 shows the standard regression coefficients, which 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

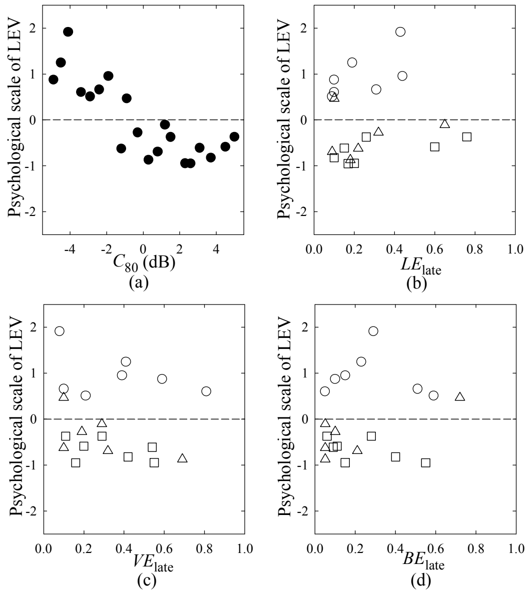

Figure 3: *Psychological scale of LEV in Experiment 1, ○:C_{80}=–5〜–2* dB*, △:C_{80}=–2〜+2* dB*, □:C_{80}=+2〜+5* dB.

Table 2: *The result of multiple regression analysis between perceived LEV and C_{80} and three directional late energy ratios in Experiment 1, significant at $p < 0.005$.*

Multiple correlation coefficient	Standard regression coefficients			
	C_{80}	LE_{late}	VE_{late}	BE_{late}
0.932	-0.967	0.630	0.223	0.393

the multiple correlation coefficient is 0.932, the accuracy of this analysis is very satisfactory. The absolute value of standard regression coefficient is the highest for C_{80}. Namely, this means that the contribution of the ratio of late energy to early one to LEV is highest. Furthermore, let us consider the contribution of the DLRs. The coefficient of LE_{late} is the highest, and the coefficients of VE_{late} and BE_{late} are 35 and 62 percents of that of LE_{late}, respectively. These tendencies agree with the previous results of the experiments performed under the condition of constant C_{80}.

From these discussions, it is found that the ratio of late energy to early one has the largest effect on LEV. Concerning directional late energy ratios, it is reconfirmed that LE_{late} strongly affects LEV, but VE_{late} and BE_{late} are also effective for LEV at the rate of approximately 30 to 60 percent of the effect of LE_{late}.

4. Experiment 2

The object of the second experiment was to investigate the effect of DLR on perceived LEV using sound fields with late sounds arriving from arbitrary directions, and to clarify whether or not the contribution of late energy with a single directional component is valid when the late sound consists of plural directional energy components.

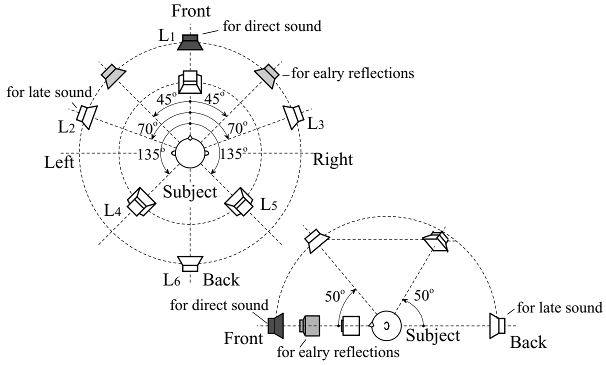

Figure 4: *Arrangement of loudspeakers in Experiment 2.*

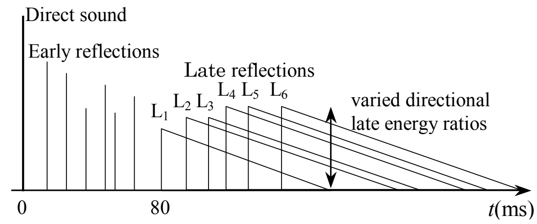

Figure 5: *Structure of the sound fields used in Experiment 2. Late sound consists of plural directional energy components.*

Table 3: *Seven sound fields used in Experiment 2.*

Stimulus No.	*BSPL* (dB)	Directional late sound energy ratio			
		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

4.1. Experimental conditions

Figure 4 shows the arrangement of the loudspeakers in Experiment 2. Six loudspeakers were located for late sounds. The late sounds except from behind the listener (L_6) consist of plural directional components.

The structure of the sound fields is shown in Fig. 5. The directional late energy ratios, LE_{late}, VE_{late} and BE_{late} were varied keeping the total level of late sound constant.

Experiment 2 consisted of two separate tests, namely, Experiments 2(a) and (b), according to the values of C_{80} which were set at -3 and 0 dB. As given in Table 3, seven kinds of sound fields were used in each test. All combinations of seven stimuli, namely, twenty-one pairs, were presented to seven subjects. Each subject was tested individually to judge each pair of stimuli eight times, and thus, a total of 168 judgments were made.

4.2. Results and discussions

The results of conformity tests with the Thurstone Case V model showed that the experimental data was significant at a level below 1%. The standard of judgment was

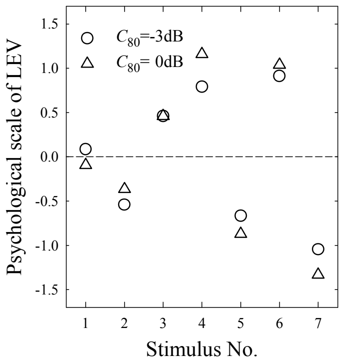

Figure 6: *Psychological scale of LEV in Experiments 2(a) and 2(b).*

agreed upon by all subjects at a level below 5% of significance. The psychological interval scales for LEV are plotted in Fig. 6, according to C_{80} values of -3 and 0 dB. As mentioned above, the significance of the difference in LEV is discussed on the basis of the jnd of LEV.

Comparing the two stimuli with the highest value of LE_{late}, nos. 4 and 6 (LE_{late} = 0.60), although VE_{late} and BE_{late} are changed, the differences in LEV between them are not psychologically significant (less than 0.68) for any C_{80}. This means that LE_{late}affects on LEV strongly. Meanwhile, comparing another set of stimuli such as nos. 3 and 6, although the difference of LE_{late}between the two is large, the differences in LEV between them are not psychologically significant. Thus, the perception of LEV is complicatedly related to the directional late energy ratios, and it cannot be simplistically explained only with one directional parameter.

Therefore, multiple regression analyses were done for two conditions of C_{80} 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 4 shows the results of the multiple regression analyses. The standard regression coefficient of LE_{late} is the highest for any C_{80}. The coefficients of VE_{late} are 28 and 44 percents of those of LE_{late}, and the coefficients of BE_{late} are 50 and 60 percents of those of LE_{late} for C_{80} values of -3 and 0 dB, respectively. This tendency agrees with the results of our previous experiment [4](named Experiment 0), in which all of the late energy had a single directional component, namely, with the arrival directions restricted to lateral, frontal, back and overhead. Figure 7 shows the comparison between measured LEV in Experiment 2 and predicted LEV by using the regression equations that have been obtained from the previous Experiment 0. The correlation coefficients between them are about 0.93 or more for any C_{80}. The result of this experiment gives good agreement with the predicted value.

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

Table 4: *The results of multiple regression analyses between perceived LEV and three directional late energy ratios in Experiment 2, significant at p<0.005.*

C_{80} (dB)	Multiple correlation coefficient	Standard regression coefficients		
		LE_{late}	VE_{late}	BE_{late}
-3	0.980	1.558	0.433	0.783
0	0.910	1.686	0.739	1.012

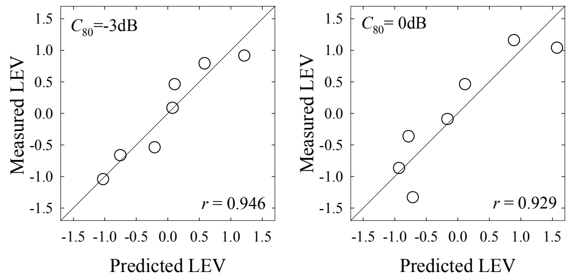

Figure 7: *Comparison between measured LEV in Experiment 2 and predicted LEV by the previous regression equation[4], r : correlation coefficient.*

5. Conclusions

In the first experiment, the result shows that the total late energy affects LEV most strongly, and it is reconfirmed that the late lateral energy ratio strongly affects LEV, but late overhead and back energy ratios are also effective for LEV. In the second experiment, it is found that the degree of the contribution of late energy with a single directional component to LEV is valid also when the late sound consists of plural directional components.

From these results, it can be concluded that both the total late sound energy and DLR should be considered for the perception of LEV. Further research on the optimum conditions for the directional distribution of late sound is needed.

6. Acknowledgments

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7. References

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