

# The directional properties of late arriving sound and listener envelopment in concert halls

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## 1. Introduction

Spatial Impression (SI) is well known as an important factor in the subjective evaluation of concert halls. Marshall<sup>1)</sup> reported that the early lateral reflections are important. Jordan<sup>2)</sup> and Barron and Marshall<sup>3)</sup> suggested objective predictors which are related spatial impression to the early lateral reflections. After the discovery of the importance of early lateral reflections on perceived SI, many works has done. But most authors have not differentiated between envelopment and apparent source width. In more extensive studies, Morimoto and Maekawa<sup>4)</sup> confirmed that there are at least two distinct dimensions to SI, apparent source width (ASW) and listener envelopment (LEV).

Also, in his work, Bradley<sup>5)</sup> found that both overall level and spatial distribution are very important to the sense of LEV and to find a simple measure which accounts for both the level and spatial distribution components of LEV, he suggested one such measure which is the relative level of the late lateral energy,  $LG_{80}$ .

On the other hand, after the discovery of the importance of early lateral reflections, most work has ignored the effects of other directional components on LEV. Furuya and Fujimoto<sup>6)</sup>, using simulated sound fields, carried out tests that examined the effects of early reflections from upside on auditory envelopment. Furthermore, there are some workers who suggested the effects of other directional components on LEV. For example, Morimoto and Iida<sup>7)</sup> suggested front/back energy ratio as a measure for envelopment and Hanyu and Kimura<sup>8)</sup> proposed SBTs, quantifying the spatial distribution of reflections using point of gravity time  $T_s$  for each direction.

However, early studies had tended to these objective measures were mostly obtained using a simple plane sound fields so it isn't confirmed whether these objective measures can be applied to real concert halls or not.

In this paper, the author performed two subjective experiments, using sound fields simulated in an anechoic room. The first experiment was performed with an objective measure of inter-aural cross-correlation (IACC) in order to predict whether LEV is perceived equally in two kinds of sound fields with horizontal or vertical components of late arriving sound.

The second experiment was designed to examine that LEV is only affected by lateral late sound level, with constant  $LG$  and an investigation of the influence on LEV, varied late sound levels whose directional properties are lateral, front, vertical and back. As independent variables: the relative level, Strength  $G$ , and the angular distribution of late arriving sound levels were varied.

## 2. Experiment

In this subjective experiment was intended to examine that whether LEV is influenced equally in two kinds of sound fields, which are consisted of horizontal directional component of late sound and vertical directional component of late sound, or not.

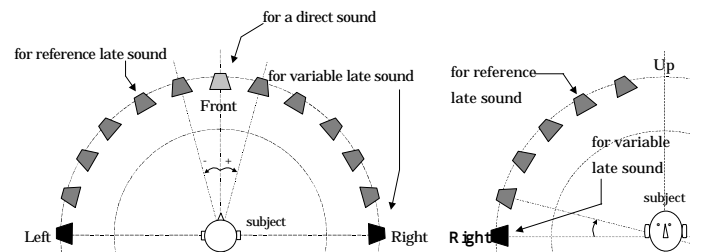
### 2.1 Method

A total of two experiments were conducted using

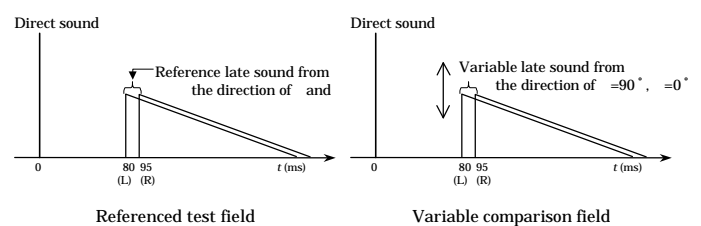
simulated sound fields in an anechoic chamber. Depending upon the experiment 13 loudspeakers were used to radiate sounds that consisted of a simulated direct sound and late arriving sounds. Using programmable digital reverberators and equalizers, the experimental setup allowed independent control of angular distribution of the late arriving sound send to each loudspeaker.

The set up of the loudspeakers in the anechoic room is illustrated in Fig.1. All tests were in the form of adjustment by subject and subject was asked to equate pairs of sound fields, One is reference sound field and the other is variable sound field, with regard to LEV by controlling the late arriving sound level. Using an attenuator, subjects could toggle between the two sound fields of each pair as many times as they wished until they had decided on their response.

The stimulus used for all of tests was an anechoic orchestral recording consisting of the 10s of Bizet's Menuet de suite No.2 "L'Arlesienne". Five students, 22 to 29 years of age with normal hearing sensitivity, acted as subjects for both tests and there was always a short practice session before each test to ensure that the subjects were familiar with the requirements of each test.



**Fig.1** Arrangement of loudspeakers in experiment



**Fig.2** Signal configuration used as stimuli.

### 2.2 Experimental conditions

The structure of the impulse responses are shown in Fig.2. The onset of the late arriving sound was delayed by 80ms (relative to the direct sound) and they were directly delivered to the left loudspeakers and to the light loudspeakers with a time delay of 10ms. The reverberation time(RT) is 1.8s.

There are two kinds of test to variable directional properties of late arriving sounds. One experiment is consisted of five pairs of late arriving sound whose angle attributions are that  $\theta = \pm 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$ . The other is consisted of five pairs of late arriving sound whose angle attributions are that  $\theta = \pm 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$ .

Acoustical conditions of reference sound field for each test are shown in Table . An objective measure of LEV , ICC (without A-weighting) which is calculated from impulse response obtained using a dummy head, was used.

In this Table,  $ICC_0$  and  $ICC_{80}$  are respectively defined as that  $ICC_0$  (the total sound) is when  $t_1=0$  and  $t_2 =500s$  and  $ICC_{80}$  (the late arriving sound) is when  $t_1=80$  and  $t_2 =580s$ . Loudness were obtained by  $BL$  <sup>9)</sup> (binaural level), using a sound pressure level with dummy head.  $L_{Aeq}$  by music was adjusted throughout each test an average level of approximately 62 dBA. In each experiment, there are 5 comparison pairs and subject rated each test by 4 times.

### 2.3 Results and discussion

The results of two experiments are given in Fig.3, with the mean scores of ICC and the 99% confidence limits which was measured by dummy head( Neumann KU100).

The results of this study indicate that in first experiment, most of variable sound fields have a similar tendency that of reference sound fields, even though, the cases of  $\phi =30^\circ \sim 40^\circ$  in variable sound fields show a little different tendency. It is likely that subject regard ICC (without A-weighting) as one of objective measures on judging LEV and it is now clear that lateral directional component of late arriving sound is most effective on perceived LEV.

Furthermore, in the second experiment, they have a little different tendency compared to the result of first experiment. Namely, ICC values in variable sound fields are smaller than that of reference sound fields, which change by 0.1. It assumed that vertical directional component of late arriving sound seems to be more attributable to judge LEV than that of horizontal one. Accordingly, both horizontal and vertical directional components of late arriving sound are important factors on perceived LEV.

### 3. Experiment

Two experiments were designed to examine the relation between the directional properties of late arriving sound and LEV. The relative sound level, Strength G, and the angular distribution of the late arriving sound levels were varied as independent variables.

#### 3.1 Method

Two experiments were conducted using simulated sound fields in an anechoic chamber. The set up of the loudspeakers in the anechoic room is illustrated in Fig.6.

All tests were in the form of paired comparisons and subjects were simply asked to identify the one they perceived to have greater LEV between each pair of sound fields. Tests used between six and eight subjects who are students studying in architectural acoustics and there was always a short practice session before each test to ensure that the subjects were familiar with the requirements of each test.

Experiments were automated and computer controlled randomly the changes to the next sound fields. The stimulus used in all the tests was same as Experiment and it was repeated at average level of approximately 62 dBA at the listener's position.

#### 3.2 Experiment -1

The first experiments was an investigation of whether only LEV is related to the level of later arriving lateral energy or not, while  $LG_{80}$  were kept constant.

##### 3.2.1 Experiment conditions

Nine loudspeakers were used to radiate sounds that

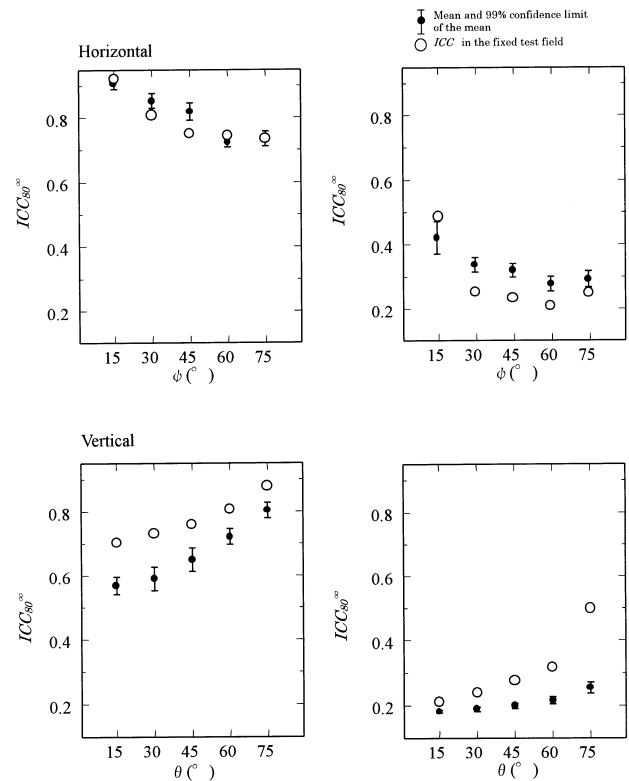
consisted of direct sound (one loudspeakers), early reflections (two loudspeakers), and late arriving sound (six loudspeakers): for two lateral late sounds, one front late sound, one rear late sound, two vertical late sounds.

**Table** Acoustical conditions of reference test field.

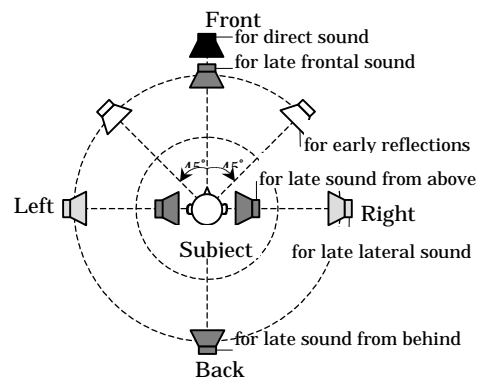
	$ICC_0$	$ICC_{80}$	$C_{80}(\text{dB})$	$BL(\text{dBA})$	$L_{Aeq}(\text{dBA})$
$15^\circ$	0.922	0.486	- 3.2	64.5	62.5
$30^\circ$	0.808	0.263	- 3.1	64.7	62.6
$45^\circ$	0.751	0.244	- 2.7	65.0	62.8
$60^\circ$	0.744	0.219	- 2.6	65.0	62.3
$75^\circ$	0.734	0.261	- 1.8	65.2	62.0

	$ICC_0$	$ICC_{80}$	$C_{80}(\text{dB})$	$BL(\text{dBA})$	$L_{Aeq}(\text{dBA})$
$15^\circ$	0.705	0.211	- 1.9	65.6	60.5
$30^\circ$	0.731	0.238	- 2.2	65.4	61.0
$45^\circ$	0.760	0.275	- 2.7	65.1	61.3
$60^\circ$	0.807	0.317	- 2.8	64.6	61.5
$75^\circ$	0.879	0.499	- 3.5	65.0	61.3



**Fig.3** Relation between ICC and angle.



**Fig.4** Arrangement of loudspeakers in Exp. -1.

Fig.5 shows the structure of the impulse responses that were used in the experiments. The signal from the front loudspeaker contained the direct sound, the six early reflections (0~80ms,  $LE=0.16$ ), while the left and right ( $L, R = \pm 45^\circ$ ) loudspeakers each contributed three early reflections. As well, late arriving sounds(80~ ms) from four directions (Lateral, Front, Vertical, Back) were added.

The total of sound fields were seven and which of them were combinations of directional properties of late arriving sounds: only lateral late sound (No.1), lateral + front late sounds (No.2), lateral + front + vertical late sounds (No.3), lateral + vertical late sounds (No.4), lateral + vertical + rear late sounds (No.5), lateral + back late sounds (No.6) and only lateral late sound (No.7), while  $LG_{80}$  was changed in 3dB. Thus, stimulus No.1~6 are constant  $LG_{80}$  and stimulus No.2~7 are constant  $G_0$ .

To know about late sounds energy of other directional components, the author defined as late front energy level,  $FG_{80}$ , late vertical energy level,  $VG_{80}$ , late back energy level,  $BG_{80}$  with using the definition of  $LG_{80}$ . Each of them was measured with the figure-of-eight microphone which was positioned toward the location of the source of each late sound.

Acoustical conditions of seven sound fields are shown in Table . Music source was adjusted an average level of 61.9~62.9 dBA ( Stimulus No.1 is 60.5 dBA ) and the early-to-late arriving sound energy ratio,  $C_{80}$ , is keeping constant in -0.4~0.1 dB ( Stimulus No.1 is 6.0 dB ).

Test had 42 pairs, including reversals of stimulus and each test was divided into two times( 21 pairs ) to reduce the proper time. Six subjects were used and each subject listened to 168 pairs ( 21 pairs  $\times$  8 times ).

### 3.2.2 Results and discussion

The psychological scales of LEV were obtained using the Thurstone Case model. The tests of goodness of fit indicated that all measured values significant( $p < 0.001$ ). Here  $p$  is the probability of these effects occurring by chance. Before calculating the psychological scales of LEV, the tests of consistency and concordance were checked. As results, the consistency test indicates that all subjects have a significant ( $p < 0.05$ ) ability to discriminate and also the concordance test indicates that they significantly judge LEV with a common standard of judgement.

The results of the experiment with the psychological scales of LEV are given in Fig.6. LEV scales of stimulus No.1~6 indicated that there were significant main effects on LEV, while  $LG_{80}$  is constant. There is little difference between stimulus No.1 (lateral) and stimulus No.2 (lateral+front) by 0.95 change in LEV scales and grate difference between stimulus No.1 (lateral) and stimulus No.6 (lateral+back) by 2.99 change in LEV scales. Therefore, they show that LEV is not affected by only  $LG_{80}$ .

Furthermore, the difference LEV scores between stimulus No.2~7 and stimulus No.3 indicated that LEV is influenced by 3dB change in  $G_0$ . The stimulus No.2~7 with constant  $G_0$  when the direction of late sounds is varied, there are significant differences on LEV scores. Compared to stimulus No.2, LEV scores varied by 0.92, 2.04, 3.20 in stimulus No.4~7. Accordingly, LEV is most influenced by the lateral sound and also vertical, back sound have a significant effect on perceived LEV.

### 3.3 Experiment -2

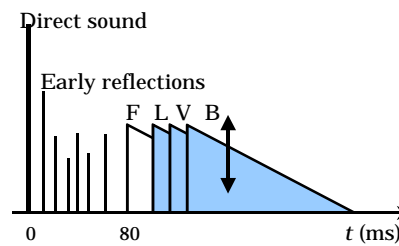


Fig.5 Signal configuration used in Exp. -1.

Table 7 sound fields used in experiment -1.

Stimulus	Directional late sound levels (dB)				
	$G_0$	$LG_{80}$	$FG_{80}$	$VG_{80}$	$BG_{80}$
1	4.6	-1.1	-	-	-
2	7.4	-1.4	3.5	-	-
3	7.2	-0.9	0.7	-0.6	-
4	7.5	-1.2	-	1.8	-
5	6.8	-1.7	-	-0.9	1.0
6	7.3	-1.2	-	-	3.1
7	7.8	4.4	-	-	-

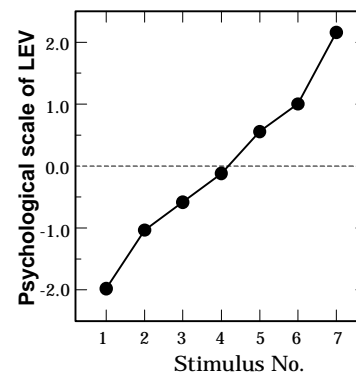


Fig.6 Psychological scale of LEV in Exp. -1.

The second experiment was an investigation of the effects on LEV, while late arriving sound level and angular distribution were varied.

### 3.3.1 Experiments conditions

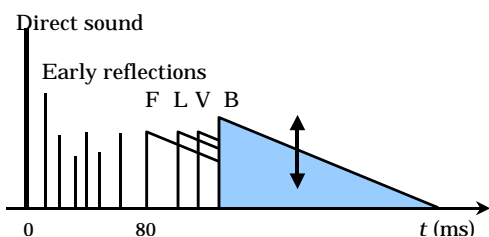
The structure of sound fields is illustrated in Fig.7. The signal is consisted of direct sound, six early reflections (0~80ms,  $LE=0.16$ ), and late arriving sounds(80~ ms) which is the same as experiment -1.

Four types of experiment, with varying angular distribution of late sounds, were conducted. Namely, on the basis of one sound fields which is consisted of lateral, front, vertical and back late sounds, there are four types of experiment conditions. The first one is that only late lateral level is changed(Exp. -2a). The second is that only late front level is changed(Exp. -2b). The third is that only late vertical level is changed(Exp. -2c). Finally, the case of only late back level is changed(Exp. -2d).

Acoustical conditions of 13 sound fields for each test are shown in Table . Music source was adjusted an average of 61.2~63.7dBA and reverberation time is 1.8s. Each test had 6pairs and eight subject were used. Subjects rated each test by eight times.

### 3.3.2 Results and discussion

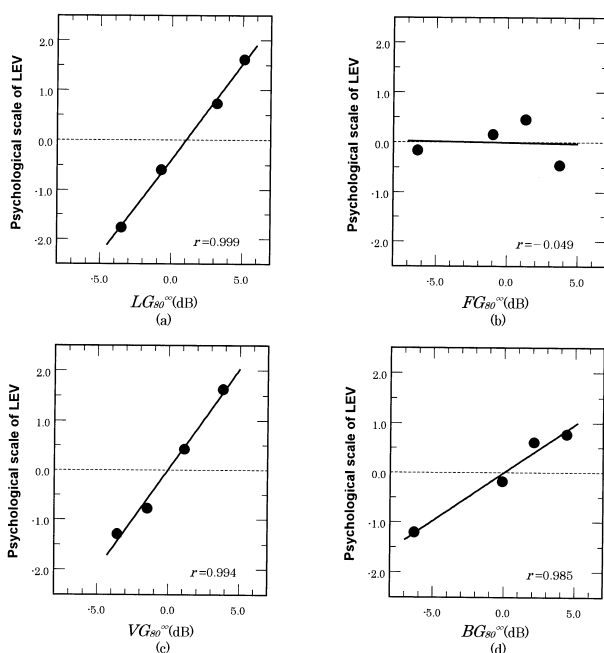
The psychological scales of LEV were obtained using the Thurstone Case model. The tests of goodness of fit indicated that all measured values significant( $p < 0.001$ ). The results of tests of consistency and concordance were same as experiment -1.



**Fig.7** Signal configuration used in experiment -2.

**Table 13** sound fields used in experiment -2.

Stimulus	Directional late sound levels (dB)				
	$G_0$	$LG_{80}$	$FG_{80}$	$VG_{80}$	$BG_{80}$
1	5.0	<b>-3.5</b>	<b>-6.3</b>	<b>-3.6</b>	<b>-6.3</b>
2	5.7	<b>-0.7</b>	-6.7	-3.7	-6.7
3	6.8	<b>3.2</b>	-6.3	-3.4	-6.3
4	8.1	<b>5.1</b>	-5.9	-3.3	-5.9
5	5.5	-3.5	<b>-1.0</b>	-3.5	-6.3
6	6.3	-3.2	<b>1.3</b>	-3.3	-6.3
7	7.8	-3.5	<b>3.7</b>	-2.8	-6.3
8	5.2	-3.5	-6.7	<b>-1.5</b>	-6.7
9	6.5	-3.4	-6.0	<b>1.1</b>	-6.0
10	7.7	-3.2	-6.3	<b>3.8</b>	-6.3
11	5.4	-3.8	-6.3	-3.6	<b>-0.1</b>
12	6.7	-3.1	-6.3	-3.3	<b>2.1</b>
13	7.5	-3.4	-6.3	-3.2	<b>4.4</b>



**Fig.8** Psychological scale of LEV versus four directional late levels in experiment -2.

The results of the experiment with the psychological scales of LEV are given in Fig.8. Compared to stimulus No.0, LEV scores varied by 3.38(Exp. -2a), 0.61(Exp. -2b), 2.92(Exp. -2c), 1.98(Exp. -2d) in each test. Namely, There are significant effects on LEV with other direction of late sound except front direction. Accordingly, LEV is most influenced by the lateral sound and also vertical, back sound have a significant effect on perceived LEV.

#### 4. Conclusions

The first experiment was performed with an objective measure of inter-aural cross-correlation(IACC) in order to examine that listener envelopment is perceived equally in two kinds of sound fields with horizontal or vertical components of late arriving sound. As results, vertical

properties of late sound have more higher effects on perceived LEV than horizontal one. Also, in this experiment so simple sound fields were used to predict listener envelopment. The judgment of LEV, with the more complicated sound fields and other objective measure except ICC is considerable.

The second experiment was intended to examine that listener envelopment is only affected by lateral late sound level, with constant  $LG$  and an investigation of the effect on listener envelopment, varied late sound levels whose directional properties are lateral, front, vertical and back. The results of experiment ,while constant  $LG_{80}$  , listener envelopment is significantly affected by other directions of late arriving sounds and the influence of late lateral arriving sound on listener envelopment is highly significant.

Furthermore, other directional components of late sounds such as vertical and back are also have significant effects on perceived listener envelopment. Accordingly, the results of this study show that LEV is not affected by only lateral components of late sounds. In order to account for the predictor measure of listener envelopment , each directional components of late sounds must be considered.

According to the results of experiments, the late lateral directional information is an important factor to make the sense of being enveloped by sound as confirmed in pervious works and other directional properties are also have a significant effects on perceived LEV. It seems to be that the objective predictor of listener envelopment, the late lateral sound level , is considerable to measure LEV and to control listener envelopment, both overall level and other directional informations of late arriving sounds must be considered.

#### ACKNOWLEDEMENTS

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