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Arrival direction of late sound and listener envelopment

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Abstract

The purpose of this study is to investigate the relation between the arrival direction of late sound and perceived listener envelopment (LEV). In this paper, two kinds of psychological experiments are conducted with three-dimensional simulated sound fields in an anechoic room. Firstly, the effect of late energy arriving from four fundamental directions on perceived LEV is individually investigated. The results show that the lateral sound level gives the highest correlation with LEV, while late sound arriving from overhead and behind the listener also correlates very strongly with LEV. Secondly, whether or not the different sound fields with a constant level of late lateral energy lead to significant differences in perceived LEV is examined. The results clearly indicate that LEV is significantly distinguished due to the late sound having non-lateral components. From these experiments, it is concluded that not only the late lateral sound, but also the late sound from other directions, such as overhead, back and frontal, contributes to LEV to a greater or lesser degree. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Spatial impression is one of the most important psychological factors that aid in the evaluation of the sound field in concert halls. Since Marshall [1] argued about the importance of early lateral reflections in concert halls, many works have been

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done on the relation between the subjective degree of spatial impression and the reflections arriving from the side directions of listeners. For example, some acoustical indices which aim at the lateral energy ratio, such as lateral efficiency *LE* and lateral energy fraction *LF*, were proposed by Jordan [2] and Barron [3]. On the other hand, it was made clear by Morimoto and Maekawa [4,5] and Bradley and Soulodre [6] that spatial impression consists of two aspects, namely, 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 the apparent sound source. Due to the verification of the distinction between these two aspects, an ambiguousness of the term 'spatial impression', which had been confusedly used to describe various aspects until its verification, was swept away. In addition, some related works [7–9] have shown that ASW is influenced by early lateral reflections and that LEV is strongly dependent on late arriving lateral energy.

With such a background, as for LEV, late lateral sound level LG_{80}^{∞} was proposed by Bradley [9] as a simple measure that could best predict listener envelopment, which he intended to account for both sound pressure level and spatial information.

On the other hand, 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. The reason is that they do not contribute to spatial impression on the basis of binaural interdependence. Concerning an acoustic index in which spatial information except for lateral energy is considered, some research on a front/back energy ratio was conducted by Morimoto [10,11] and recently on spatially balanced T_S SBT_S by Hanyu [12]. All of these physical measures, however, were derived from psychological experiments using simulated plane sound fields that consisted of reflections and reverberation placed only in a horizontal plane, including the lateral axis through the listener's ears. Therefore, 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 at all. 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.

Although it is accepted that LEV is strongly influenced by late arriving lateral energy, 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 late lateral sound energy alone. The purpose of this study, therefore, lies basically in clarifying the relation between the arrival direction of late sound and listener envelopment. In this paper, two kinds of psychological experiments are conducted with simulated sound fields in an anechoic room. Firstly, in Experiment 1, the effects of level changes in late sound arriving from four directions, namely, lateral, frontal, back, and overhead, on perceived LEV are individually investigated. Secondly, in Experiment 2, the question of whether or not the late lateral sound level alone is related to LEV is fundamentally examined using sound fields with a constant level of late lateral energy.

2. Method

2.1. Apparatus

Two kinds of psychological experiments were conducted using simulated sound fields in an anechoic chamber. Fig. 1 shows the arrangement of the loudspeakers in the 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. This setup allowed for independent control of the level and the time delay of the reflections and the reverberation sent to each loudspeaker. A loudspeaker for direct sound was in front of the listener and two loudspeakers for early reflections within 80 ms after the direct sound 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 six loudspeakers. Four of them were located at azimuth

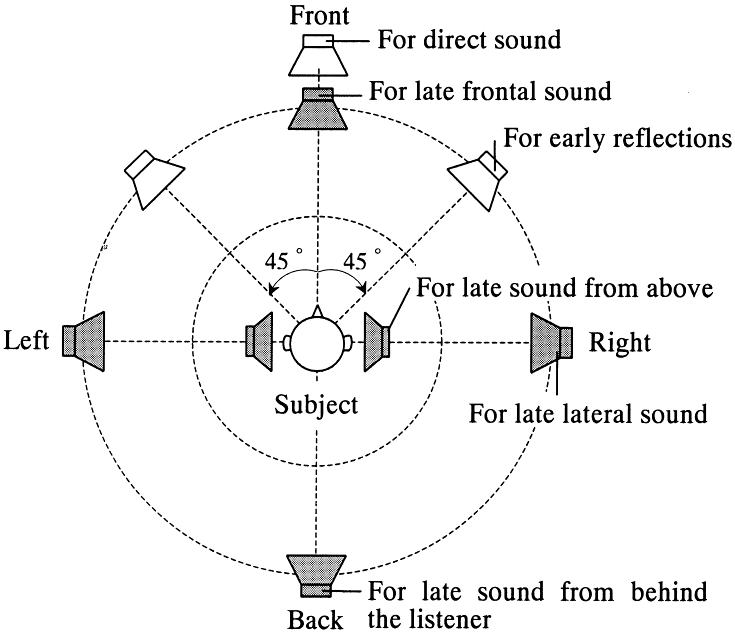

Fig. 1. Arrangement of loudspeakers in an anechoic chamber. The loudspeakers for direct sound and early reflections are placed in the horizontal plane of the listener's head. The six loudspeakers for late sound are located at 0° (frontal), ±90° (lateral), 180° (behind) relative to the direct sound source in the horizontal plane, and at an elevation angle of 80° and azimuth angles of ±90° above the listener (overhead).

angles of ±90° (left and right), 0° (front), and 180° (back) relative to the listener on the horizontal plane. The two vertical loudspeakers were symmetrically located at an elevation angle of 80° and azimuth angles of ±90°. They could not be set just above the listener since there was a structural constraint on the frame from which the loudspeakers were suspended. However, the lateral energy component from these vertical loudspeakers was small enough to be negligible, because the level of the lateral component was about -15 dB $[10\log(\cos 80^\circ)^2]$ relative to the total energy radiated from these loudspeakers. There were no loudspeakers under the listener, because the late sound arriving from below is almost nonexistent in the sound field of real auditoria, and thus, there was no need to consider it. In this way, a total of six loudspeakers for late sound were arranged to individually control three directional components of late sound energy. They had lateral, longitudinal, and vertical components, which present the fundamental spatial distribution of late energy. All the loudspeakers were equidistant (1.5 m) from the listener.

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'Arlésienne, 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, 22–25 years old, with normal hearing sensitivity. Before the experiments, the term 'listener envelopment' was explained to them with a conceptual illustration and comments, which indicated that listener envelopment was defined as a listener's sensation of the space being filled with sound images other than the apparent sound source. 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 listener envelopment 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.

2.3. Psychological analysis

In both experiments, psychological interval scales of LEV were constructed from experimental results by the method of Thurstone's Case V [13]. 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 is calculated when a probability of judgement for $S_i > S_j$ is equal to 75%.

Before calculating the psychological interval scales, a consistency of each subject's judgement and an agreement of judgement among subjects were analyzed from the responses. The subjects' ability to discriminate between sound fields was tested by counting the number of circular triad, which meant an inconsistency in the comparative judgement for three pairs of three stimuli (e.g. $S_1 < S_2$, $S_2 < S_3$, and $S_3 < S_1$). Then, whether one subject had the same judgement as the others in the paired comparisons was investigated. The degree of agreement among judgements was obtained by calculating the number of the pair of subjects who had the same judgement for a pair of stimuli, and by summing up the numbers for all pairs of stimuli. The significance was evaluated by a χ^2-test.

2.4. Objective measures

The acoustical quantities of the sound fields were calculated from the overall impulse responses obtained using omni-directional, figure-of-eight, and dummy-head microphones. In this paper, late lateral sound level LL_{80}^{∞}, late frontal sound level FL_{80}^{∞}, late overhead sound level VL_{80}^{∞}, and late back sound level BL_{80}^{∞} were introduced to determine the directional components of late sound energy. These were defined as the relative level of each directional late energy arriving more than 80 ms after the direct sound to the direct sound energy. Similarly, L_0^{∞} was defined as the relative level of total energy to the direct sound energy. The direct sound energy was held constant in all experiments.

The listening sound pressure level was measured using a dummy head microphone (Neumann KU100) for the music source. The binaural *SPL* [14] 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 the dummy head.

3. Experiment 1

The object of the first experiment was to investigate the individual effect of four directional components of late energy, namely, lateral, frontal, back, and overhead, 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 impulse responses 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 the value of lateral efficiency *LE* [2] was 0.16. The onset of the late sound was delayed by more than 80 ms relative to the direct sound so as not to affect the early portion of the sound field. The reverberation time was set at 1.8 s.

Experiment 1 consisted of four tests, namely, Experiments 1(a)–(d), according to the four arrival directions of the late sound. As given in Table 1, each test was

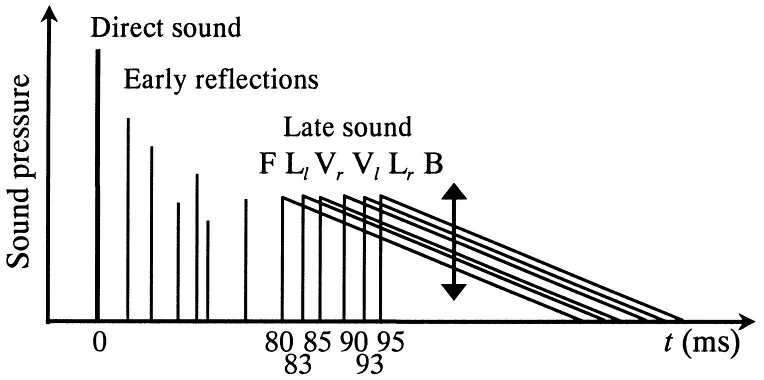

Fig. 2. Structure of the sound fields used in Experiments 1 and 2 (F = frontal, L = lateral, V = overhead, and B = behind; subscripts *l* and *r*: left and right). In Experiment 1, each directional late sound is independently varied while the others are kept constant. In Experiment 2, late sound from four directions is added so that the total level of late sound is kept constant, except for stimulus no. 1. The late lateral sound levels are identical except for stimulus no. 7.

Table 1
Thirteen sound fields used in Experiment 1

Experiment no.	Stimulus no.	L_0^∞ (dB)[a]	Directional late sound levels (dB)[a]			
			LL_{80}^∞	FL_{80}^∞	VL_{80}^∞	BL_{80}^∞
Common field[b]	1	5.0	**−3.5**	**−6.3**	**−3.6**	**−6.3**
1(a)	2	5.7	**−0.7**	−6.7	−3.7	−6.7
	3	6.8	**3.3**	−6.3	−3.4	−6.3
	4	8.1	**5.1**	−5.9	−3.3	−5.9
1(b)	5	5.5	−3.5	**−1.0**	−3.5	−6.3
	6	6.3	−3.2	**1.3**	−3.3	−6.3
	7	7.8	−3.5	**3.7**	−2.8	−6.3
1(c)	8	5.2	−3.5	−6.7	**−1.5**	−6.7
	9	6.5	−3.4	−6.0	**1.1**	−6.0
	10	7.7	−3.2	−6.3	**3.8**	−6.3
1(d)	11	5.4	−3.8	−6.3	−3.6	**−0.1**
	12	6.7	−3.1	−6.3	−3.3	**2.1**
	13	7.5	−3.4	−6.3	−3.2	**4.4**

[a] All values are defined as the relative level to a direct sound energy that is kept constant in all stimuli.
[b] Stimulus no. 1 is included as a common field in all tests.

independently performed using four sound fields, including a common field (stimulus no. 1). The late sound was radiated from all directions in all the 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. The range of the total level variation was approximately 3 dB, while the ratio of early-to-late sound energy, C_{80}, was in the range of -2 to 3 dB.

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

3.2. Results and discussion

The results of the two tests on the consistency and the agreement of judgements showed that a subject's ability to discriminate between sound fields was statistically significant at a level below 5%, and that the standards of judgement were 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 directional late sound levels LL_{80}^{∞}, FL_{80}^{∞}, VL_{80}^{∞} and BL_{80}^{∞} are plotted in Fig. 3(a)–(d), respectively. It is found that LEV is positively correlated with each directional sound level, except for the late frontal sound level. The late lateral sound level, LL_{80}^{∞}, correlates most strongly with LEV, as is generally accepted. In addition, the correlation coefficients between LEV and the values of VL_{80}^{∞} and BL_{80}^{∞} exceed 0.98 in Experiments 1(c) and (d). Namely, LEV clearly becomes stronger with increases in them. This means that LEV is dependent on the 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_{80}^{∞}, 7 dB in VL_{80}^{∞} ,and 11 dB in BL_{80}^{∞}. These differences are signficantly 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 $FL_{80}^{\infty} = 1.3$ and 3.7 is more than subjective-jnd. Therefore, although the late frontal sound does not correlate with LEV, as mentioned above, 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 binaural *SPL* 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_{80}^{∞} includes the large effect of the 4-dB increase in loudness, while the difference in LEV for changes in VL_{80}^{∞} and BL_{80}^{∞} barely include the effect.

From these discussions, it can be concluded that not only the late lateral sound level but also the late sound levels from above and behind the listener correlate with LEV positively and strongly. Additionally, although there is no correlation between the late frontal sound level and LEV, it cannot be found that the late frontal sound does not contribute to LEV at all.

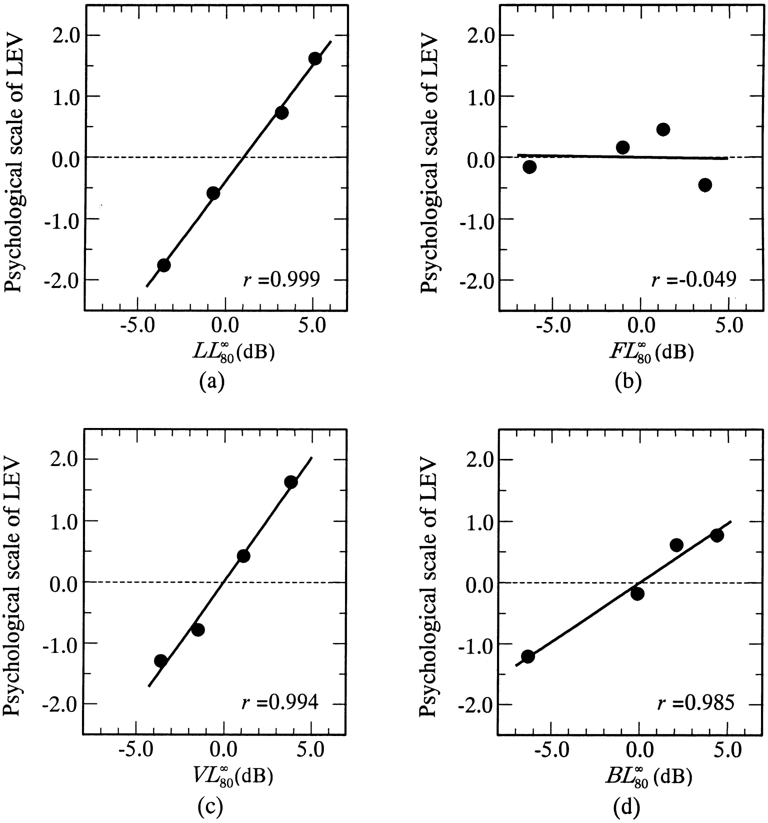

Fig. 3. Psychological scale of LEV versus four directional late sound levels in Experiment 1. *r* is a correlation coefficient.

4. Experiment 2

The object of the second experiment was to investigate whether or not the different sound fields with a constant level of lateral energy led to significant differences in perceived LEV.

4.1. Experimental conditions

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 late energy was delayed by more than 80 ms relative to the direct sound, and the reverberation time was 1.8 s.

As given in Table 2, seven kinds of sound fields were used in Experiment 2, considering the combination of four directions of late sound incidence, that is, lateral (L), frontal (F), overhead (V), and back (B) directions. The late sound was radiated from the direction of (L) in stimulus no. 1, (L + F) in stimulus no. 2, (L + F + V) in

Table 2
Seven sound fields used in Experiment 2

Stimulus no.	L_0^∞ (dB)[a]	Directional late sound levels (dB)[a]			
		LL_{80}^∞	FL_{80}^∞	VL_{80}^∞	BL_{80}^∞
1	4.6	−1.1	–[b]	–	–
2	7.4	−1.4	3.5	–	–
3	7.2	−0.9	0.7	−0.6	–
4	7.5	−1.2	–	2.8	–
5	6.8	−1.7	–	−0.9	1.0
6	7.3	−1.2	–	–	3.1
7	7.8	4.4	–	–	–

[a] All values are defined as the relative level to a direct sound energy that is kept constant in all stimuli.
[b] The directional energy is not added ($-\infty$ dB).

stimulus no. 3, (L + V) in stimulus no. 4, (L + V + B) in stimulus no. 5, (L + B) in stimulus no. 6, and (L + L) in stimulus no. 7. The late energy of stimuli nos. 1 and 7 was presented only from a lateral direction. In stimuli nos. 2–7, the late sound from directions other than lateral, the level of which was constant at about 3 dB relative to the direct sound, was added to the sound field of stimulus no. 1 having only lateral energy. Namely, stimuli nos. 2– 7 consisted of late sound coming from different directions, but had the same energy level. Consequently, the late lateral level of stimulus no. 7 was approximately 6 dB higher than that of stimulus no. 1. Furthermore, the total level of late sound was adjusted so that C_{80} was approximately 0 dB in the stimuli except for stimulus no.1. In this way, late lateral sound level LL_{80}^∞ was constant at the scatter of ±0.4 dB in stimuli nos. 1–6, and total sound level L_0^∞ was almost constant in stimuli nos. 2–7.

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 judgements was made. The A-weighted binaural *SPL*s with the music source were 63 dB for stimulus no. 1, 64 dB for stimuli nos. 2–6, and 66 dB for stimulus no. 7 at the listening point.

4.2. Results and discussion

The subjects' ability to discriminate between sound fields was statistically significant at a level below 5% for the total number of response data (6 subjects × 8 times = 48), and the standard of judgement 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 are plotted in Fig. 4.

First, let us consider the results for stimuli nos. 1–6. Although the late lateral sound levels of those stimuli are identical, the results clearly show that there are significant differences in perceived LEV between stimulus no. 1 and stimuli nos. 2–6. Namely, LEV for stimuli nos. 2–6 is stronger than that for stimulus no. 1. The minimum difference in scale values from stimulus no. 1 with only lateral energy is

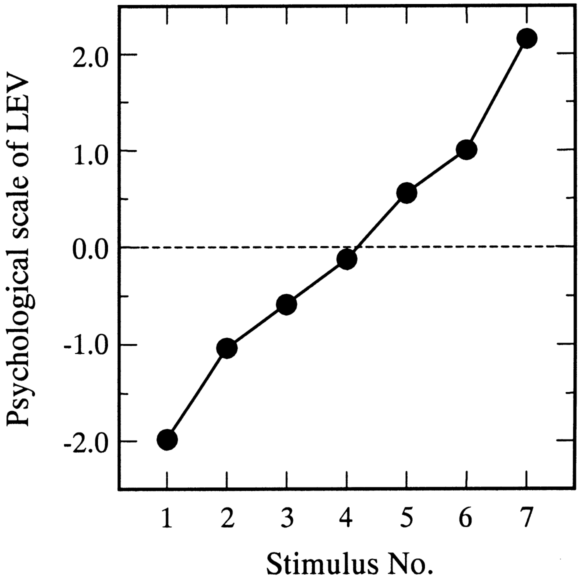

Fig. 4. Psychological scale of LEV in Experiment 2. Late lateral sound level LL_{80}^{∞} is constant in stimuli nos. 1–6, and total sound level LL_{0}^{∞} is constant in stimuli nos. 2–7.

0.95 for stimulus no. 2 with the late frontal energy, while the maximum difference is 2.99 for stimulus no. 6 with additional late energy from behind the listener. Since these differences exceed the subjective-jnd of 0.68, they are psychologically significant in the discrimination of LEV. Thus, the subjective changes in LEV are distinctly perceived in stimuli nos. 1–6, even though the late arriving lateral energy does not change. Additionally, the difference in binaural *SPL* between stimulus no. 1 and stimuli nos. 2–6 is only 1 dB. Therefore, it is thought that the effect of the difference in binaural *SPL* on LEV for these stimuli is very small.

Next, let us consider the results for stimuli nos. 2–7 for which the total sound level is kept constant. The difference in scale values is 0.92 between stimuli nos. 2 and 4, 1.13 between stimuli nos. 4 and 6, and 1.16 between stimuli nos. 6 and 7. These differences are more than the subjective-jnd. Therefore, it can be considered that the differences in LEV for stimuli nos. 2–7 depend on the arriving directions of late sound added to sound field no. 1. In other words, the results indicate clearly that not only does late sound from directions other than lateral contribute to LEV, but that the degree of contribution increases in order of lateral, back, overhead, and frontal. As expected, the LEV for stimulus no. 7 is the strongest where LL_{80}^{∞} is about 6 dB higher than the others. It should be noted, however, that the difference in LEV between stimulus no. 7 and stimuli nos. 2–6 includes the effect of a 2-dB difference in binaural *SPL*.

From these discussions, it can be concluded that late sound from directions other than lateral is also related to LEV. Namely, although late lateral sound definitely has the largest effect on the LEV, late sound arriving from above the listener, behind the listener, and in front of the listener also influences the perceived LEV to a greater or lesser degree.

5. Conclusion

The relation between the arrival direction of late sound and listener envelopment was psycho-acoustically confirmed using three-dimensional sound fields with late energy arriving from four fundamental directions. The first experiment clearly showed that late sound from lateral, overhead and back directions correlated with LEV positively and strongly. In the second experiment, the LEV perceived in different sound fields with the same lateral energy was significantly distinguished because of late sound added from directions other than lateral. In addition, the results indicated that the degree of contribution to LEV increased in order of lateral, back, overhead, and frontal. From these results, it can be concluded that not only late lateral sound, but also late sound from directions other than lateral, especially from back and overhead, contribute to listener envelopment.

The present results suggest that the degree of perceived listener envelopment cannot be explained only with a measure depending on the level of late arriving lateral energy. Therefore, the idea that reflections arriving from directions other than lateral must be excluded for creating a sense of listener envelopment seems to be very risky in acoustical design. In other words, the spatial effect of lateral sound energy should not be exaggerated, because an excess amount of reflection energy from only a partial direction might cause an unnaturalness in the room impression. It is necessary to pursue the indices which can account not only for the absolute energy level, but also for a ratio of various directional energy to total energy. A well-balanced directional distribution of reflections should also be considered in the acoustical design of concert halls. Late lateral sound energy must be a predominant factor in perceiving listener envelopment. However, late sound arriving from other directions, such as overhead, is also effective in feeling a three-dimensional fullness of sound. Further research on the optimum conditions for the directional distribution of late sound is needed.

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