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Effects of frequency characteristics of reverberation time on listener envelopment

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Spatial impression perceived in a listening space comprises at least two components: one is auditory (apparent) source width (ASW) and the other is listener envelopment (LEV). Both ASW and LEV are affected not only by temporal but also by spatial structures of reflections. It has been clarified that ASW for symphony music is significantly affected by low-frequency components of source signals and reflections, but not by their high-frequency components. The objective of this work is to investigate whether LEV is affected by the frequency characteristics of source signals and reverberation sounds, which are known to contribute to the creation of LEV. In this study, three experiments were performed to clarify the effects of reverberation time (RT) and its frequency characteristics on LEV. In contrast to the case of ASW, the experimental results show that RTs both at high and low frequencies affect LEV. © *2007 Acoustical Society of America.*
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I. INTRODUCTION

Spatial impression is one of the important characteristics perceived in a listening space. It is widely accepted that the spatial impression comprises at least two components.[1-4] One is auditory (apparent) source width (ASW) and the other is listener envelopment (LEV). It is well known that both ASW and LEV are affected by not only temporal but also spatial structures of reflections.

In addition, ASW is also commonly affected by spectral structures of source signals and reflections. Barron and Marshall[5] discussed the effect of the reflection spectrum on ASW (they used the term "spatial impression" instead of ASW) for symphony music. They concluded that, for ASW, the frequency range covered by the 125 Hz to 1 kHz octaves is considered important, low frequencies being particularly important and desirable. Morimoto and Maekawa[6] examined the effect of low-frequency components of the source signal on ASW for a wide-band noise ranging from 100 Hz to 5.3 kHz, by changing the lower cutoff frequency and keeping the degree of interaural cross-correlation constant. The results showed that removing frequency components lower than 510 Hz decreases ASW markedly. Hidaka *et al.*[7] and Okano *et al.*[8] studied the effect of the low-frequency strength of the source signal on ASW for symphony music. The results demonstrated that the frequency components lower than 355 Hz affect ASW much more than those higher than 355 Hz. Morimoto and Iida[9] investigated the effect of high-frequency components of lateral reflections on ASW for a wide-band noise ranging from 200 Hz to 8 kHz by changing the higher cutoff frequency and keeping the degree of interaural cross-correlation constant. The experimental results indicated that the frequency components above 1 kHz do not contribute to the creation of ASW at all.

Naturally, typical physical measures of ASW for symphony music consider the low-frequency components. Barron[10] suggested LF_{E4}, which is the average value of early lateral energy fractions over the four octave bands from 125 Hz to 1 kHz, while Hidaka *et al.*[7] and Okano *et al.*[8] suggested $IACC_{E3}$, which is the average value of early interaural cross-correlation over the three octave bands from 500 Hz to 2 kHz.

On the other hand, the effect of spectral structures on LEV is not clearer than that on ASW. Beranek[11] suggested $IACC_{L3}$, which is the average value of late interaural cross-correlation over the three octave bands from 500 Hz to 2 kHz, as a physical measure of LEV, while Bradley and Soulodre[3] demonstrated that the late lateral sound level, which is the value summed for the four octave bands from 125 Hz to 1 kHz, best predicted LEV in their experiments. However, it is not clear whether the spectral structures of source signals and reflections affect the perception of LEV. In this study, three experiments are carried out to clarify the effects of the frequency characteristics of reverberation time on the perception of LEV.

II. METHOD

The same test method was used in the three experiments performed in this study. The music motif used for the experiments was a 7-s section of the first movement of Mozart's Divertimento in F major, K. 138 (125c) recorded in an anechoic chamber. The motif was reproduced with a limited frequency range from 100 Hz to 10 kHz.

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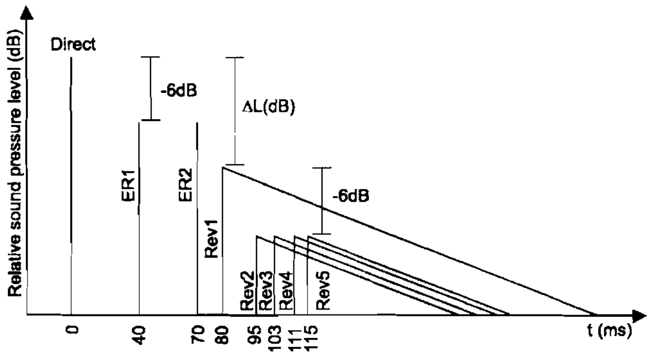

FIG. 1. Schematic diagram of impulse response of the stimulus used in the experiments.

Figure 1 shows schematically the impulse response of a stimulus. The sound field used as the stimulus consisted of a direct sound, two early discrete reflections, and five coherent reverberation sounds. The reflection delays were 40 and 70 ms and the reverberation delays were 80, 95, 103, 111, and 115 ms. The sound pressure levels of two early reflections were identical, and their relative sound pressure levels to the direct sound were −6 dB. The relative sound pressure level of the initial amplitude of the first reverberation sound was ΔL dB. The sound pressure levels of the other four reverberation sounds were identical, and their relative sound pressure levels to that of the first one were −6 dB.

Figure 2 shows the arrangement of loudspeakers. Six loudspeakers, each of which is installed in a cylindrical enclosure (diameter: 108 mm, length: 350 mm), were arranged at azimuth angles of 0 and ±45 deg from the median plane; that is, they were arranged symmetrically with respect to the aural axis, in an anechoic chamber. The distance between the center of the subject's head and the loudspeakers was 1.5 m. The direct sound was radiated from the loudspeaker at 0 deg.

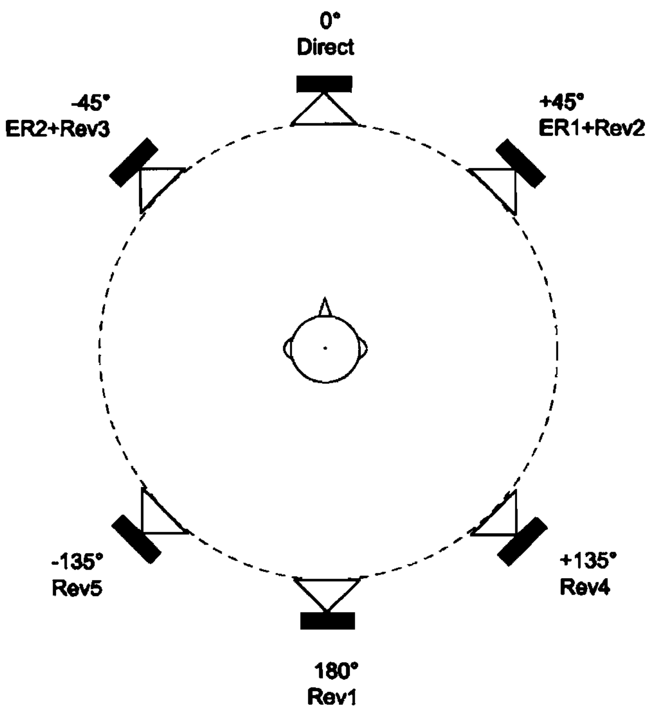

FIG. 2. Arrangement of loudspeakers in the experiments.

TABLE I. Stimuli in experiment 1.

Stimulus	Parameter		
	RT (s)	C_{80} (dB)	ΔL (dB)
1	1.0	6.0	−26.3
2	1.0	2.8	−26.3
3	1.0	0.9	−26.3
4	2.0	5.5	−26.3
5	2.0	2.7	−26.3
6	2.0	0.7	−26.3

The first and second early reflections were radiated from the loudspeakers at +45 and −45 deg, respectively. The first to fifth reverberation sounds were radiated from the loudspeakers at 180, +45, −45, +135, and −135 deg, respectively.

Paired comparison tests were performed in the experiments. The interval between the two stimuli was 2 s. Each pair of stimuli was arranged in random order and separated by an interval of 5 s. Each subject was tested individually and ten times for each pair including reversals, while seated with the head fixed in a darkened anechoic chamber. The task of the subject was to judge which LEV is greater. Before the experiments, the concept of LEV was explained to the subjects. All the subjects had sufficient experience as subjects in this kind of experiment.

The psychological scales of LEV were obtained using the Thurstone Case V model.[12,13] Gulliksen's method[13,14] was also used for incomplete data. The following must be considered in interpreting the psychological scales obtained using the Thurstone Case V model: The difference of 0.68 on the psychological scale means that the probability of discriminating the difference between two stimuli is 75%. Therefore, it is generally considered that the difference of 0.68 on the psychological scale corresponds to the just noticeable difference (jnd).

III. EXPERIMENT 1: EFFECTS OF REVERBERATION TIME ON LEV

Bradley and Soulodre[3] demonstrated that the effect of reverberation time (RT) in the range of 1.5 s on LEV was comparatively small under the condition that the early-to-late sound ratio (C_{80}) was constant. However, the effects of the amplitude of reverberation sound and RT on LEV might cancel each other out in their experiments, since the amplitudes of reverberation sounds after 80 ms were varied so that RT might be changed while keeping C_{80} constant. Here, as a preliminary experiment, it is investigated whether RT affects LEV when changing RT and C_{80} independently and keeping the relative sound pressure level of reverberation sound (ΔL) constant.

A. Experimental conditions

In this experiment, six kinds ($2\ \mathrm{RT} \times 3\ C_{80}$) of stimulus were used as shown in Table I. RT and C_{80} changed independently, keeping ΔL of all stimuli constant at −26.3 dB. The frequency characteristics of RT were flat. RT was changed using a digital reverberator (Roland SRV-3030). C_{80} was

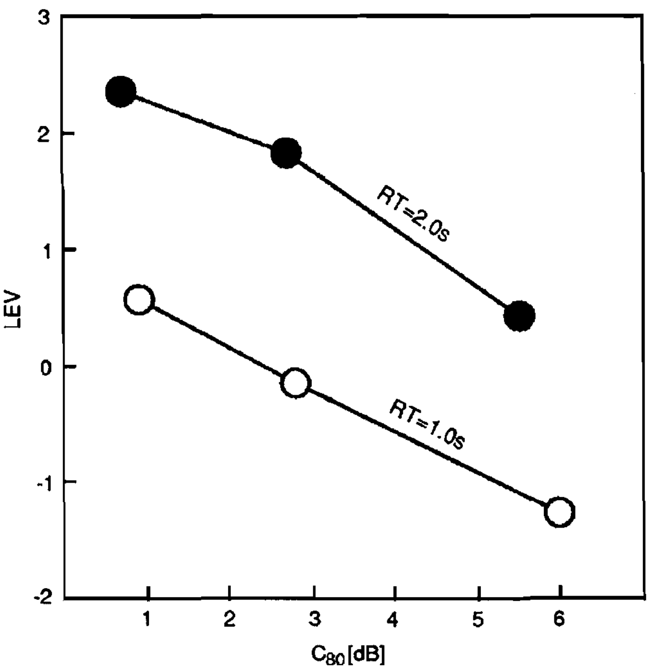

FIG. 3. Psychological scale of LEV as a function of C_{80} and as a parameter of RT in experiment 1.

controlled by changing the sound density of reverberation sound. This control technique was nothing more than an experimental one for varying C_{80}, while keeping RT, and vice versa. It included no implication about the acoustical design of real concert halls. It was verified that the change in sound density had no effect on the perception of reverberance in the experiments. Furthermore, C_{80} was measured for the overall frequency range using the music motif employed in the experiments as a measuring signal. The binaural sound pressure levels[15] of stimuli were constant at 80.0 ± 0.1 dBA slow peak, measured at two ears of a KEMAR dummy head without an artificial ear simulator (B & K Type DB-100). The degrees of interaural cross-correlation (DICC)[16] of the reverberation sounds were constant at 0.43 ± 0.03, as measured using a KEMAR dummy head without an artificial ear simulator. The late lateral sound level was not measured. However, it is readily understood that the late lateral sound levels of stimuli were constant as in the case of DICC since the directions of five reverberation sounds and the relative levels of lateral reverberation sounds to that from the rear direction were fixed. Seven students with normal hearing sensitivity participated as subjects for the experiment. Thirty pairs of stimuli including reversals were presented ten times to each subject.

B. Experimental results and discussion

In total, 2100 responses (30 pairs $\times$ 10 times $\times$ 7 subjects) were used to obtain the psychological scale of LEV. Figure 3 shows the psychological scale of LEV in experiment 1, that is, LEV with a parameter of RT and as a function of C_{80}. For each C_{80}, LEV for RT=2.0 s is greater than that for RT=1.0 s. The difference between them exceeds 0.68 for every C_{80} and is 1.68 (which means that the probability of discriminating the difference is 95.4%) at minimum when C_{80} is about 6.0. Furthermore, the differences for all three C_{80} are almost identical. This means that RT significantly affects LEV, being independent of C_{80}. Namely, LEV increases as RT becomes longer. Meanwhile, for each RT value, LEV increases as C_{80} decreases. The difference between the maximum and the minimum LEV is 1.82 (96.6%) and 1.91 (97.2%) for RT=1.0 and 2.0 s, respectively, and is far more than 0.68. This means that C_{80} also significantly affects LEV.

TABLE II. Frequency characteristics of RT for stimuli in experiment 2 (unit: s).

	Center frequency of $\frac{1}{3}$ octave band (Hz)						
Stimulus	125	250	500	1000	2000	4000	8000
	Experiment 2(a) (RT=1.0 s)						
1	0.50	0.63	0.75	0.85	0.93	1.00	1.00
2	0.66	0.77	0.77	0.91	0.94	1.00	1.01
3	1.13	1.00	1.04	1.02	0.96	1.00	1.01
4	1.82	1.28	1.19	1.06	1.01	1.06	1.99
5	2.11	1.58	1.30	1.10	1.01	1.02	1.00
6	2.34	1.82	1.41	1.10	1.03	1.02	0.99
	Experiment 2(b) (RT=2.0 s)						
1	0.49	0.92	1.21	1.61	1.81	1.91	1.93
2	1.16	1.18	1.46	1.87	1.90	1.91	1.93
3	2.20	1.93	1.91	2.03	1.96	1.92	1.94
4	2.92	2.67	2.18	2.12	1.99	1.93	1.94
5	3.33	3.22	2.45	2.17	1.98	1.91	1.94
6	3.82	3.33	2.63	2.20	2.03	1.94	1.94

IV. EXPERIMENT 2: EFFECTS OF REVERBERATION TIME AT LOW FREQUENCIES ON LEV

A. Experimental conditions

In experiment 2, the effects of RT at low frequencies on LEV were investigated for RT=1.0 and 2.0 s with flat frequency characteristics. In this experiment, six kinds of frequency characteristics of RT were used for each RT as shown in Table II. The values of RT in the table were ones measured at the point corresponding to the center of the subject's head in an anechoic chamber. RTs below around 1 kHz were changed by controlling a parameter "Low Ratio" built into the digital reverberator (YAMAHA Pro R3). This equipment can lengthen and shorten RT at low frequencies, but cannot change RT at high frequencies. For each RT, stimulus no. 3 has nearly flat frequency characteristics of RT. At low frequencies, stimuli nos. 1 and 2 have shorter RT than stimulus no. 3 and, conversely, stimuli nos. 4–6 have longer RT than stimulus no. 3.

C_{80}'s were constant at 0 dB. ΔL's were constant at -25.6 ± 0.5 dB and -27.6 ± 0.8 dB for RT=1.0 and 2.0 s, respectively. The binaural sound pressure levels were constant at 79.9 ± 0.1 and 80.0 dBA for RT=1.0 and 2.0 s, respectively. DICC of the reverberation sounds were constant at 0.32 ± 0.03. A paired comparison test was carried out separately for each RT. Six students with normal hearing sensitivity participated as subjects for the experiment. A paired

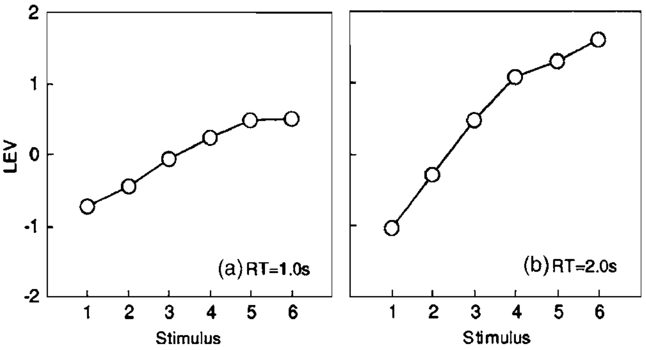

FIG. 4. Psychological scale of LEV as a function of frequency characteristics of RT for (a) RT=1.0 s and (b) 2.0 s in experiment 2. In this experiment, RT at frequencies lower than 1 kHz either shorten or lengthen. For stimulus no. 3, each RT has nearly flat frequency characteristics. As the stimulus number decreases from no. 3, RT at frequencies lower than 1 kHz shorten, and vice versa. The precise frequency characteristics of RT of each stimulus are shown in Table II.

comparison test was carried out separately for each RT. For each RT, 30 pairs of stimuli including reversals were presented ten times to each subject.

B. Experimental results and discussion

In total, 1800 responses (30 pairs × 10 times × 6 subjects) were used to obtain the psychological scale of LEV for each RT. Figure 4 shows the psychological scale of LEV in experiment 2, that is, the effects of RT at low frequencies on LEV. For both RT, LEV increases as RT at low frequencies becomes longer and vice versa. Here, let us compare those results with LEV for stimulus no. 3 with flat frequency characteristics of RT.

For RT=1 s, the decrease for stimulus no. 1 with the shortest RT at low frequencies is 0.672 (74.9%) and the increases for stimuli nos. 5 and 6 with longer RT at low frequencies are 0.558 (71.2%) and 0.567 (71.5%), respectively. These differences are slightly smaller than the difference of 0.68 (75%) corresponding to jnd. The decrease for stimulus no. 2 and the increase for stimulus no. 4 are 0.380 (64.8%) and 0.316 (62.4%), respectively. It cannot be considered that these differences can be discriminated.

Meanwhile, for RT=2 s, the decreases for stimuli nos. 1 and 2 with shorter RT at low frequencies are 1.501 (93.3%) and 0.750 (77.3%), respectively. These differences can be distinctly discriminated. The increase for stimulus no. 4 is 0.611 (72.9%), which is slightly smaller than the difference of 0.68 (75%) corresponding to jnd. However, the increases for stimuli nos. 5 and 6 with longer RT at low frequencies are 0.833 (79.7%) and 1.123 (86.9%), respectively. It can be considered that these differences can be discriminated distinctly.

Furthermore, for each RT, the differences in LEV between stimulus no. 1 with the shortest RT and stimulus no. 6 with the longest RT at low frequencies are 1.24 (89.3%) and 2.62 (99.6%) for RT = 1 and 2 s, respectively. The subjects could discriminate clearly the differences.

On the basis of the above experimental results, it can be concluded that RT at low frequencies affects LEV significantly when RT at low frequencies becomes longer and shorter.

TABLE III. Frequency characteristics of RT for stimuli in experiment 3 (unit: s).

	Center frequency of $\frac{1}{3}$ octave band (Hz)						
Stimulus	125	250	500	1000	2000	4000	8000
1	1.05	1.54	1.68	1.89	1.97	2.01	2.00
2	1.44	1.57	1.73	1.91	1.97	2.01	2.01
3	2.00	1.97	2.02	1.99	1.98	1.99	1.98
4	2.03	2.05	2.03	1.99	1.82	1.63	1.34
5	2.04	2.04	2.01	1.97	1.84	1.57	1.23

V. EXPERIMENT 3: EFFECTS OF SHORTENING REVERBERATION TIME AT EITHER LOW OR HIGH FREQUENCIES ON LEV

A. Experimental conditions

In experiment 3, the effects of shortening each RT at low and high frequencies on LEV were investigated for RT =2.0 s with flat frequency characteristics. In this experiment, five kinds of frequency characteristics of RT were used as shown in Table III. Table III shows the frequency characteristics of RT of the stimuli used in the experiment. RT below around 500 Hz and above around 4 kHz were shortened by controlling parameters "LF DAMP" and "HF DAMP," respectively, built into the digital reverberator (Roland SRV-3030). This equipment can shorten each RT at low and high frequencies, but cannot lengthen them. For stimulus no. 3, RT has nearly flat frequency characteristics. Stimuli nos. 1 and 2 have shorter RT at low frequencies and conversely, stimuli nos. 4 and 5 have shorter RT at high frequencies than stimulus no. 3. The values of RT on the table were ones measured at the point corresponding to the center of the subject's head in an anechoic chamber.

C_{80} were constant at 0 dB. ΔL were constant at -26.3 ± 0.3 dB. The binaural sound pressure levels of stimuli were constant at 79.9 ± 0.1 dBA. DICC of the reverberation sounds were constant at 0.43 ± 0.03. Five students with normal hearing sensitivity participated as subjects for the experiment. Twenty pairs of stimuli including reversals were presented ten times to each subject.

B. Experimental results and discussion

In total, 1000 responses (20 pairs × 10 times × 5 subjects) were used to obtain the psychological scale of LEV. Figure 5 shows the psychological scale of LEV in experiment 3, that is, the effects of shortening RT at either low or high frequencies on LEV. LEV decreases as RT at low frequencies becomes shorter, in contrast to LEV for stimulus no. 3 with flat frequency characteristics of RT. The decreases for stimuli nos. 1 and 2 are 0.839 (79.9%) and 0.774 (78.1%), respectively, which are large enough to be discriminated. Namely, RT at low frequencies significantly affect LEV. This result coincides with those of experiment 2.

Meanwhile, LEV also decreases as RT at high frequencies becomes shorter, in contrast to LEV for stimulus no. 3

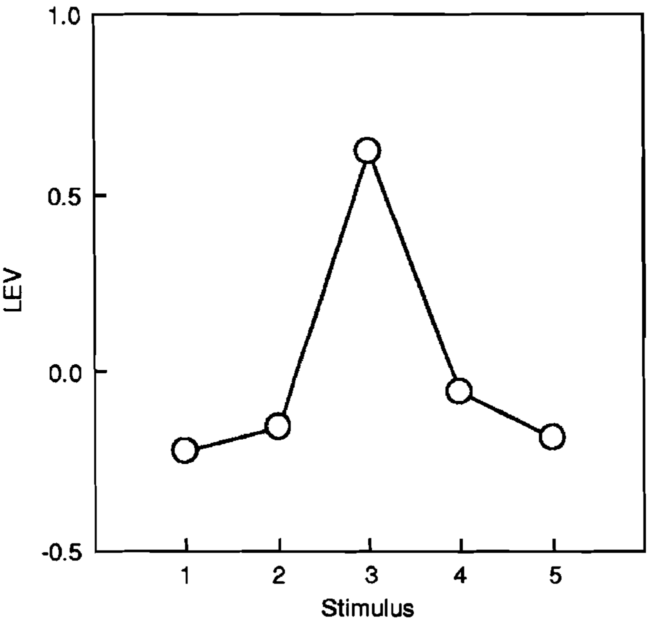

FIG. 5. Psychological scale of LEV as a function of frequency characteristics of RT in experiment 3. In this experiment, RT at frequencies either lower or higher than 1 kHz shorten. For stimulus no. 3, RT has flat frequency characteristics. As the stimulus number decreases from no. 3, RT at frequencies lower than 1 kHz shorten and, as the stimulus number increases from no. 3, RT at frequencies higher than 1 kHz shorten. The precise frequency characteristics of RT of each stimulus are shown in Table III.

with flat frequency characteristics of RT. The decreases for stimuli nos. 4 and 5 are 0.677 (75.1%) and 0.804 (80.4%), and they are almost the same as those obtained when shortening RT at low frequencies and large enough to be discriminated. This phenomenon is different from the perception of ASW that is affected by low-frequency components but not high-frequency components. In other words, high-frequency components must be considered in evaluating LEV.

VI. CONCLUSIONS

The effects of reverberation time (RT) and the frequency characteristics of RT on listener envelopment (LEV) for symphony music were investigated. Three subjective experiments were performed to clarify the effects, keeping other physical parameters, the relative sound pressure level of reverberation sound to the direct sound, the early-to-late sound energy ratio (C_{80}), and the degree of interaural cross-correlation, constant.

In the first experiment, RT was changed, keeping its frequency characteristics flat. The results indicate that RT significantly affects LEV, being independent of C_{80}. LEV increases as RT becomes longer. In the second experiment, RT at low frequencies were shortened and lengthened. The results demonstrate that LEV significantly decreases as RT at low frequencies shortened and vice versa. In the third experiment, both RT at low and high frequencies were shortened. The results show that RT at high frequencies, as well as those at low frequencies, significantly affect LEV.

In conclusion, the experimental results show that RT affects LEV, being independent of the early-to-late sound ratio (C_{80}), and that RT at high as well as low frequencies affect LEV, in contrast to the case of ASW, which is affected by the low-frequency components, but not the high-frequency ones.

In this study, the effects of lengthening RT could not be investigated owing to technical difficulties. However, it can be inferred from the results of all the experiments that lengthening RT at low as well as high frequencies increases LEV.

ACKNOWLEDGMENTS

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