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Effect of sound strength and IACC on perception of listener envelopment in concert halls

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ABSTRACT

The effects of sound strength (G) on perceived listener envelopment (LEV) at audience positions were investigated in different concert halls. The impulse responses were measured in the halls with different size. Anechoic violin sound was convolved with the impulse responses and the sound pressure level (SPL) was varied from 68.0 to 75.5 dBA in 1.5 dB step. A total of 18 sound stimuli with different interaural cross correlation (IACC) values of 0.13, 0.37, and 0.57 were provided for auditory tests. Results of subjective experiments indicated that LEV was not realized when SPL was less than around 70dBA even though IACC was 0.13. This means that the effect of IACC on LEV perception could be relatively small when the SPL is not large enough.

INTRODUCTION

To evaluate the acoustic quality in concert halls, it is important to identify the subjective measures for sound fields. Schroeder et al. [1] reproduced the hall acoustics in a testing room for listeners and found two factors to be significant for subjective preference: reverberation time (RT), and interaural cross-correlation (IACC). From subjective questionnaires regarding sound fields in British concert halls, Barron [2] found that significant subjective factors were RT, the early decay time (EDT), the early-to-late sound index (C80), the total sound level (G), and the early lateral energy fraction (LF). These factors, related to spatial impression, have been found to be important for the subjective evaluation of sound quality in concert halls.

The importance of the spatial attributes of sound field has been concerned by many researchers in terms of the shape and cross-section of concert halls since the 1960s. Then, two objective measures were determined: IACC and LF. Keet [3] found that apparent source width (ASW) is correlated with the cross-correlation function, when listening level is fixed. Damaske and Ando [4] defined IACC as the maximum absolute value of the interaural cross-correlation function. They found that IACC corresponds to the subjective diffuseness of the sound field. Barron [5] investigated the importance of early lateral reflections for spatial impression. He found that the degree of spatial impression is related to the ratio of lateral to non-lateral sound arriving within 80 ms of the direct sound. By investigating the effects of reflection delay, direction, level and spectrum on spatial impression, LF was defined [6].

Spatial impression also depends on the sound level. Keet [3] found that ASW widens by about 1.5 degrees for each decibel increase in sound pressure level. According to Barron's investigation (through use of a questionnaire [2]), spatial impression in concert halls can be explained by LF and total sound level. Hidaka et al. [7] found that the sound strength (G) at low frequencies has much greater influence on ASW as compared to G at high frequencies. It was also found that ASW changes about 2 degrees for each decibel change in G at low frequencies.

The concept of spatial impression is divided into two aspects [8]: apparent source width (ASW), the width of a sound image fused temporally and spatially with the direct sound, listener envelopment (LEV), the degree of fullness of sound increasing early lateral sound levels (GEL), LEV increases with increasing late-arriving sound energy, but decreases when early-arriving sound is added. Early-arriving sound is a more effective masker of late sound for LEV than is late-arriving sound for ASW. LEV also increases with the level of late-arriving nonlateral sounds. Morimoto et al. [9] showed that reflections from behind a listener increase LEV and the late reflections are more effective in LEV than early ones.

Most previous studies have used simulated sound fields in testing rooms to show the contribution of acoustical parameters to the spatial impression. But the clear criteria of the acceptance level and lower limit, useful for the design of the sound field of concert halls, have not been fully revealed. Therefore, the present study began by evaluating the acoustical qualities of the Sejong Chamber Hall both in the hall and in a laboratory. The in-situ experiment results were compared with those of the laboratory experiments to validate the results. Then, the minimum reflected sound level (Gr) was investigated to find out the acceptable LEV.

ACOUSTIC QUALITY EVALUATIONS

In-situ experiment

A subjective test was conducted in the Sejong Chamber Hall (476 seats). Eight seats were selected considering the distribution of SPL and IACC (Figures 1 and 2). An anechoic source (violin solo, 15 s) was reproduced from an omnidirectional loudspeaker on the stage. The sound level was calibrated so that the Leq was 75 dBA at Position 1 (the nearest seat for recording). Ten subjects were asked to evaluate six subjective attributes at each seat, using 5-point scales: clarity, reverberance, loudness, ASW, LEV, and overall impression. There was no other audience than the test subjects.

Regarding the correlation between the objective parameters and subjective attributes, high correlation was observed for the loudness and RT, C80, Ts, Gr, late G at low frequencies (G_{LL}) and 1-IACC$_{E3}$. Clarity was also highly correlated with RT, C80, Ts, Gr, G_{LL} and 1-IACC$_{E3}$. LEV and overall impression showed significant correlation with 1-IACC$_{L3}$. As for the correlation coefficients among subjective attributes, overall impression indicated significant correlation with ASW and LEV. Also, clarity was significantly correlated with loudness perception.

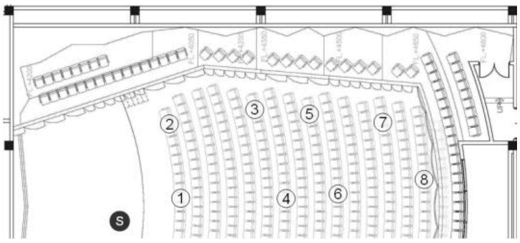


Figure 1. Source and recording positions of small sized hall

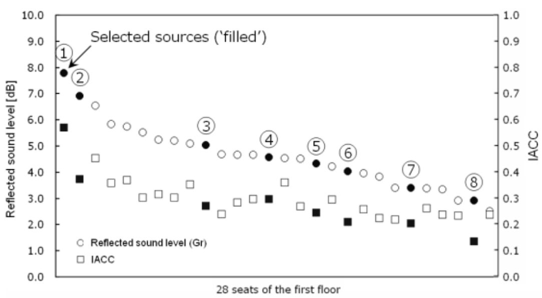


Figure 2. Sound level and IACC of measured positions including selected ones

Table 1. Correlation coefficients between objective parameters and subjective attributes in in-situ experiment (* p<0.05; ** p<0.01)

	RT	EDT	C80	Ts	Gr	G_{LL}	1-IACC$_{E3}$	1-IACC$_{L3}$
Clarity	-0.73*	-0.52	0.85*	-0.72*	0.92**	0.90**	0.92**	0.41
Reverberance	0.03	-0.02	-0.34	0.36	-0.35	-0.28	-0.49	0.15
Loudness	-0.77*	-0.44	0.90*	-0.75*	0.96**	0.90**	0.98**	0.46
ASW	-0.47	-0.12	0.40	-0.32	0.53	0.38	0.46	0.51
LEV	-0.47	-0.48	0.37	-0.28	0.45	0.43	0.30	0.74*
Overall impression	-0.28	-0.49	0.36	-0.38	0.38	0.32	0.19	0.83*

Table 2. Correlation coefficients among subjective attributes in in-situ experiment (** p<0.01)

	Clarity	Reverberance	Loudness	ASW	LEV
Clarity		-0.45	0.91**	0.49	0.45
Reverberance			-0.39	0.18	0.48
Loudness				0.56	0.38
ASW					0.81**
Overall impression	0.26	0.41	0.28	0.75**	0.87**

Laboratory experiment

The sound fields at the eight positions were used for in-situ experiment: they were were reproduced in a test room by using a stereo dipole system. The violin music piece used in the in-situ experiment was also the source. In the laboratory, the subjects in the previous experiment were asked to evaluate the sound field at eight seats. They also evaluated the subjective attributes of clarity, reverberance, loudness, ASW, LEV, and overall impression. The test subjects used a 5-point evaluation scale. The accuracy of the sound reproduction by the stereo dipole system was confirmed in terms of the objective parameters: RT, EDT, C80, and IACC. The differences of all the parameters in the real and virtual sound fields were within the just noticeable difference that was shown in the previous study. The sound presentation level was 75 dBA in Leq.

Regarding the correlation between the objective parameters and subjective attributes, loudness showed significant correlation with C80, Ts, Gr, G_{LL} and 1-IACC$_{E3}$. Clarity showed significant correlation with C80, and ASW was only highly correlated with RT. LEV showed high correlation with C80, Gr, 1-IACC$_{L3}$, whereas overall impression showed no significant correlation with resulting objective parameters in this laboratory experiment.

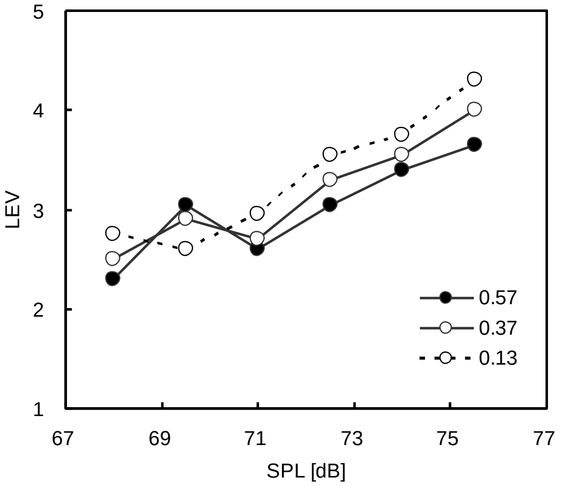
Table 3. Correlation coefficients between objective parameters and subjective attributes in the laboratory experiment (* p<0.05; ** p<0.01)

	RT	EDT	C80	Ts	Gr	GLL	1-IACCE	1-IACCL
Clarity	-0.40	-0.25	0.82*	-0.58	0.67	0.49	0.60	0.21
Reverberance	0.32	0.32	-0.61	0.44	-0.67	-0.58	-0.88*	-0.11
Loudness	-0.65	-0.26	0.90*	-0.75*	0.92*	0.80*	0.85*	0.43
ASW	-0.80*	0.05	0.69	-0.57	0.62	0.54	0.39	0.27
LEV	-0.19	-0.61	0.80*	-0.66	0.78*	0.63	0.50	0.74*
Overall impression	0.21	-0.64	0.42	-0.33	0.36	0.26	0.01	0.70

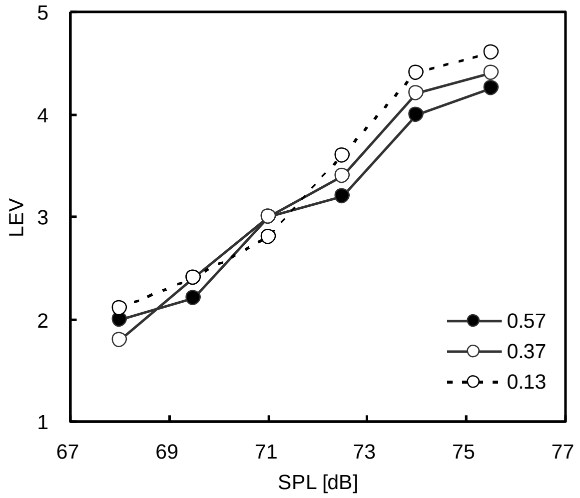
Table 4. Correlation coefficients among subjective attributes in laboratory experiment (* p<0.05; ** p<0.01)

	Clarity	Reverberance	Loudness	ASW	LEV
Clarity		-0.50	0.69	0.66	0.61
Reverberance			-0.71**	-0.19	-0.39
Loudness				0.78**	0.75**
ASW					0.65
Overall impression	0.30	0.04	0.28	0.33	0.84**

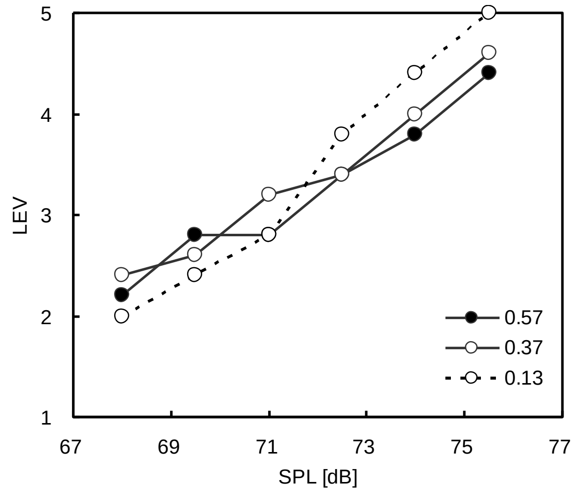
Comparing the t-test results of the in-situ and laboratory experiments, only the loudness evaluation was significantly different. This means that subjective evaluation results of the two experiments are in a good agreement validating each other. The reason for the difference of loudness perception is that the subjects' concentration on the loudness of the stimuli in the laboratory was high compared to in-situ experiment.



(a) RT, 1.2 s



(b) RT, 1.7 s



(c) RT, 2.0 s

Figure 3. LEV as a function of SPL obtained from 5-point scale test

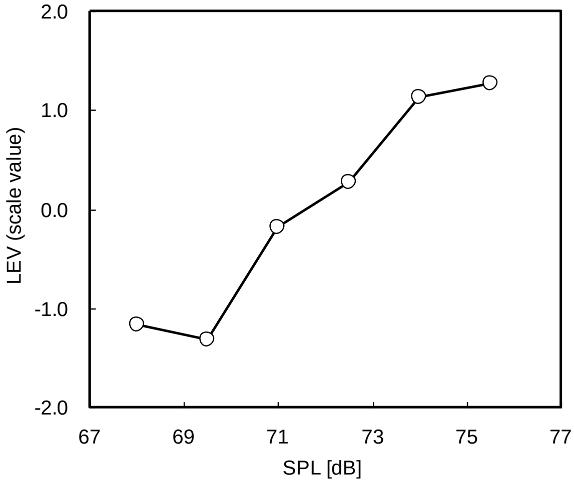


Figure 4. LEV as a function of SPL, paired comparison test (IACC, 0.37; RT, 1.2 s)

EFFECT OF SPL AND IACC ON LEV PERCEPTION

Small sized hall

Subjective judgments on LEV perception were conducted in a testing room. The same anechoic violin source was used in the laboratory. Experimental sounds were convolved with the impulse responses recorded at positions 1, 2, and 8 (see Figure 1). The presentation level of the test signals was varied from 68.0 to 75.5 dBA in 1.5 dB steps. The values of IACC were 0.13, 0.37, and 0.57, providing three different sound fields. Nineteen subjects were asked to evaluate each sound field in terms of LEV on 5-point scales. Level 3 of the 5-point scale was set to the acceptable level in terms of LEV. In other words, level 1 or 2 explain the LEV perception is not acceptable or not desirable, whereas, levels above level 3 indicate satisfactory or good enough LEV.

Figure 3 shows the results of LEV judged by the nineteen subjects. The responses of more than level 3 were found in the case where the sound levels were more than around 70 dBA. Below this level, the effect of IACC on LEV became less. When the SPL was larger than about 70 dBA, LEV increased as the SPL increased and IACC decreased.

To investigate the effect of the SPL on LEV in more detail, LEV was also evaluated by the paired-comparison method. The same violin music source was used for this paired comparison evaluation. The sound fields were reproduced by using the same stereo dipole system. This time IACC was fixed at 0.37 (a common value in the main audience area of good halls), and the sound pressure level was varied from 68.0 to 75.5 dBA in 1.5 dB steps. Eighteen subjects participated and consistency tests indicated that ten of the subjects ($p<0.01$) were able to distinguish various degrees of LEV. Figure 4 shows the scale value of LEV as a function of the sound level. The results of the paired comparison test showed that the scale value of LEV perception increased as the SPL was increased above 70 dBA, similar to the result of the 5-point scale test.

Large sized hall

Subjective judgments were conducted by using sound sourced obtained from large sized hall – Sejong Grand Theater (3,000 seats). The violin source in the previous experiments was convolved with the impulse responses, which have around 1.6 s of RT, recorded at positions 6, 10, and 16 in Figure 5. The presentation level of the test signals was varied from 68.0 to 75.5 dBA in 1.5 dB steps with the same manner of previous experiments. The values of IACC were 0.47, 0.59, and 0.71, providing three different sound fields. Twenty subjects were asked to evaluate each sound field in terms of LEV, using paired comparisons.

Figure 6 shows the scale value of LEV as a function of the sound level. The results of the paired comparison test showed that scale value of LEV perception increased as the SPL was increased in all the levels from 65.0 to 78.5 dBA. Overall tendency of relations between LEV and SPL were maintained compared to the results from small sized hall. But in this case, LEV was well perceived in relatively lower SPL ranges.

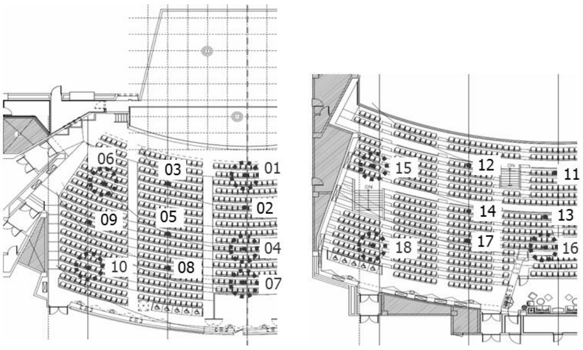


Figure 5. Source and recording positions of large sized hall

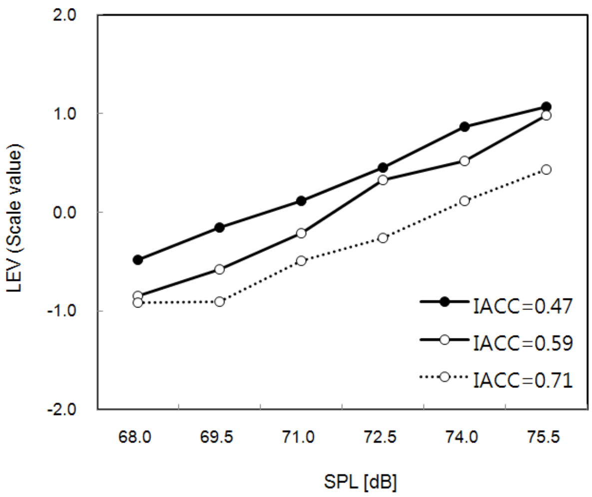


Figure 6. LEV as a function of SPL, paired comparison test (RT, 1.6 s)

CONCLUSIONS

In both cases of in-situ and laboratory experiments, loudness was well correlated with C80, Ts, Gr, G_{LL} and 1-$IACC_{E3}$, and LEV was highly correlated with 1-$IACC_{L3}$. The relationship between loudness perception and spatial impression for the laboratory experiment was much stronger than that of the in-situ experiment when considering correlation results among subjective attributes. In both cases of the in-situ and laboratory experiments, LEV was highly correlated with overall impression. The results of the laboratory experiment showed that spatial impressions, LEV and ASW, were highly correlated with loudness.

From the results of the 5-point scale evaluation, the sound field in terms of LEV can be improved by decreasing IACC when the sound field has a high enough sound pressure level. At a lower sound pressure level, the preference of the sound field in terms of LEV can be improved by increasing the sound pressure level. The effect of IACC on LEV is small when SPL of the sound field is below 70 dBA. The result of the paired comparison test showed that there was little difference in preference between IACC of 0.37 and 0.57. Although IACC reflects the relative level of early lateral reflections to the direct sound, the relationship between SPL, IACC, and LEV was revealed to be nonlinear. If the absolute sound level decreases, the level of early reflections also decreases. Some of the reflections under the threshold of perception seem not to contribute to LEV. These characteristics were also observed in the situation of a bigger hall.

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