Subjective and Objective Evaluation of the Scattered Sound in a 1:10 Scale Model Hall

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The acoustic properties of a multi-purpose hall were measured in a 1:10 scale model to investigate the effect of scattered reflections on its opera mode. The first measurements were made in stalls area both when diffusers were and were not present on the walls adjacent to the pit and on side walls. Approximately 40% of the wall area was covered with diffusers. The diffusers consisted of 12.5-22.5cm-high hemispheres and 25cm-high polygons with the effective range of 1 to 2kHz. It was found that the installation of diffusers in several positions close to the walls adjacent to the pit increased 1-$IACC_{E3}$. Then, subjective evaluation was conducted to investigate the effect of diffusers in each receiver position. The results of subjective test showed that scattered sounds were preferred to specular sound field.

1 Introduction

The effects of sound diffusion on room acoustics have been investigated during the last 30 years. Recent studies revealed that both early and late sounds are affected by scattered reflections [1-3]. The efforts to quantify the properties of sound-diffusing surfaces have since yielded the international standards [4].

However, there is still little study on quantification of the degree of diffusion in real sound fields. So far, the indices that have been developed that indicate the degree of diffusion in sound fields are *SDI* (*sound diffusivity index*) with visual inspection [5] and *LEV* (*Listener envelopment*, 1-$IACC_{L3}$) [6].

Thus, there are definite needs for subjective and objective research on diffusion in real sound fields. In particular, study on both early and late parts of scattered reflection in a hall is necessary to properly evaluate the degree of diffusion.

Objective measurements in a 1:10 scale model were carried out in this study according to precedents on acoustic investigation of scale models [7]. The measured binaural impulse responses were analyzed on the basis of the subjective preference theory [8]. The following four orthogonal factors have been proposed as objective temporal and spatial factors for evaluating subjective preferences: (1) the listening level (*LL*), (2) the initial time-delay gap (Δt_1) between the direct sound and the reflection with maximum amplitude, (3) the subsequent reverberation time (T_{sub}), and (4) the magnitude of the interaural cross-correlation function (*IACC*).

In this study the effect of diffusers in a 1:10 scale model was investigated both subjectively and objectively. The purpose of this study is twofold: (1) to evaluate the effect of varying the sound field on room acoustical parameters with respect to the four given acoustic factors and (2) to evaluate the quality of scattered sound in terms of subjective preference judgments.

2 Objective measurements

2.1 1:10 Scale model

A 1:10 scale model of the Gimhae Culture Arts Hall (GCAH), a multi-purpose hall under construction, was used in this study. Table 1 gives the architectural details of GCAH.

Table 1. Architectural details of GCAH

Use	Concert, opera, drama, and speech events
Plan type	Shoebox + Horseshoe
Seats	Total 1,484 seats 1st and 2nd (Stalls): 864, 3rd : 313, 4th : 307
Dimension	W × L × H: 28.5m × 31.3m × 20.4m
Volume	15,325m^3 (main hall and orchestra enclosure)
Proscenium	W: 18.0m, H: 12.0m
Pit	Depth: 7.7m, Height: 3.0m, Area: 169m^2
Adjustable elements	Absorption banner, orchestra enclosure, movable orchestra pit

The scale model consists of lacquered MDF (Medium Density Fiberboard), seats, audiences and absorption banners. The materials of each element were selected through absorption coefficient measurements using the 1:10 reverberation chamber.

2.2 Measurement set-up

The binaural impulse responses were measured in stalls area both with and without diffusers on the walls adjacent to the pit, on the side walls, and on the soffit of the side balcony in opera mode of the GCAH. The installed diffusers were 12.5, 15, 17.5, 20 and 22.5cm-high hemispheres and 25cm-high polygons. Their effective frequency range in a real scale was 1 to 2kHz. The surface density of diffusers was determined to be about 40% according to the previous study [3]. The distribution ratio for five types of diffuser was the same as 8%. Figure 1 shows two measurement conditions with and without diffuser. It was assumed that the hall made a specular sound field without a diffuser and a scattered sound field with the diffuser.

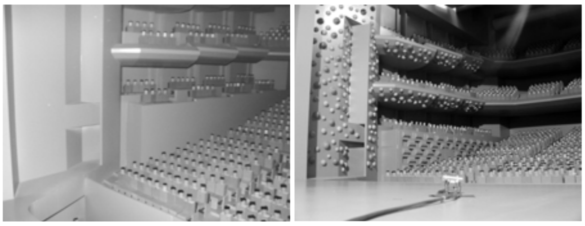


Figure 1: Measurement conditions; (Left) without diffuser and (Right) with diffuser

An electric spark source and a scale model head & torso were used as the source and receiver, respectively. A scale model head & torso consists of a Styrofoam head of diameter 21mm and two 1/8″ microphones with a nose cone installed at each ear location for binaural measurement. Several impulse responses by spark sources were recorded using an amplifier, an AD/DA converter, and a laptop computer. The average of sound waves from five trials was used.

2.3 Source and receiver positions

The source and receiver positions are shown in Figure 2. The stage source was placed at a distance of 3m from the front edge of the stage and 1m from the centerlines. The height of the sources was 1.5m above the floor. The fifteen receivers were located in the stalls, and the height of the receivers was 1.2m above the floor.

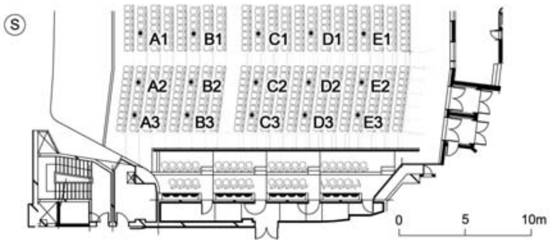


Figure 2: Locations of sources and receivers

2.4 Measurement results

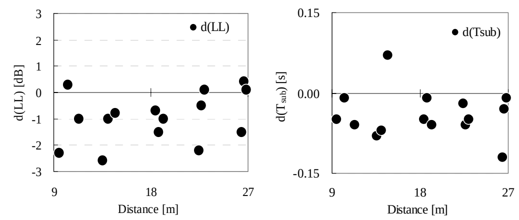
2.4.1 Four orthogonal factors

The values of four orthogonal factors measured in both conditions are shown in Table 2. *LL* and T_{sub} were averaged for 1k and 2kHz bands, considering the effective frequencies of the installed diffusers. To consider early and late parts of scattered reflection, *IACC* with different integration periods was used; $1\text{-}IACC_{E3}$ (0-80msec) and $1\text{-}IACC_{L3}$ (80-1000msec). All $1\text{-}IACC_{E3}$ and $1\text{-}IACC_{L3}$ were measured in the three octave bands with center frequencies at 500, 1k and 2kHz [9].

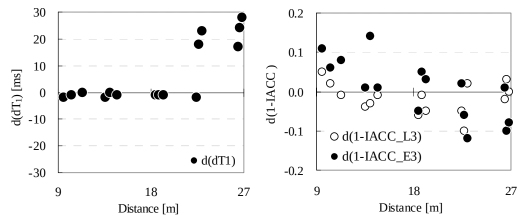
Table 2. Values of the four orthogonal factors at each position with and without diffuser

Seat	Specular sound (without diffuser)					Scattered sound (with diffuser)				
(distance) [m]	*LL* [dB]	Δt_1 [ms]	T_{sub} [s]	$1\text{-}IACC_{E3}$	$1\text{-}IACC_{L3}$	*LL* [dB]	Δt_1 [ms]	T_{sub} [s]	$1\text{-}IACC_{E3}$	$1\text{-}IACC_{L3}$
A1 (9.5)	-3.0	36	1.18	0.27	0.86	**-5.3**	**34**	**1.13**	**0.38**	**0.91**
A2 (10.3)	-3.8	23	1.00	0.50	0.86	-3.5	22	0.99	0.56	0.88
A3 (11.3)	-2.9	14	1.05	0.55	0.91	**-3.9**	**14**	**0.99**	**0.63**	**0.90**
B1 (13.6)	-3.0	32	1.12	0.56	0.91	-5.6	30	1.04	0.57	0.87
B2 (14.0)	-6.1	6	1.18	0.50	0.93	**-7.1**	**6**	**1.11**	**0.64**	**0.90**
B3 (14.7)	-5.6	8	1.05	0.65	0.91	-6.4	7	1.12	0.66	0.90
C1 (18.4)	-7.5	28	1.05	0.66	0.93	-8.2	27	1.00	0.61	0.87
C2 (18.8)	-5.7	13	0.98	0.70	0.89	-7.2	12	0.97	0.75	0.88
C3 (19.2)	-5.7	6	1.02	0.72	0.93	-6.7	5	0.96	0.75	0.88
D1 (22.4)	-5.7	20	0.87	0.71	0.84	-7.9	18	0.85	0.73	0.79
D2 (22.7)	-6.9	11	0.87	0.78	0.88	-7.4	29	0.81	0.72	0.78
D3 (23.0)	-7.8	5	0.90	0.82	0.91	-7.7	28	0.85	0.70	0.93
E1 (26.4)	-8.4	17	0.76	0.80	0.89	-9.9	34	0.64	0.81	0.87
E2 (26.6)	-9.4	10	0.84	0.85	0.84	-9.0	34	0.81	0.75	0.87
E3 (26.8)	-8.4	5	0.79	0.78	0.89	-8.3	33	0.78	0.70	0.89

As shown in Figures 3(a) and 3(b), when the diffusers were installed, the overall level (*LL*) decreased by up to 2.6dB and the subsequent reverberation time (T_{sub}) decreased by up to 0.08sec due to the absorption of diffusive surfaces, even though T_{sub} of 0.08sec was within just noticeable difference (*JND*, 10%). Δt_1 at the rear seats increased when diffusers were installed as shown in Figure 3(c). For the rear seats, the surface which provides the first reflection moved from the nearby wall to the wall close to the source. In terms of spatial diffuseness, both the values of $1\text{-}IACC_{E3}$ and $1\text{-}IACC_{L3}$ increased at the front and side seats near the source, as shown in Figure 3(d). But $1\text{-}IACC_{E3}$ showed a larger range of variance than $1\text{-}IACC_{L3}$. Also the correlation between respective differences of $1\text{-}IACC_{E3}$ and $1\text{-}IACC_{L3}$ was very low (R=0.08).



(a) Difference of *LL* (b) Difference of T_{sub}



(c) Difference of Δt_1 (d) Difference of *1-IACC*

Figure 3. The differences in the four orthogonal parameters between the scattered and specular sound fields by distance from the source

2.4.2 Impulse responses

Figure 4 shows the early impulse responses for position A1 both with and without a diffuser. The traces represent part of sound energy distributions for the first 80msec. The duration of the sound path slightly shortens, due to the proximity of the reflecting surfaces to the measuring positions. Also, the reflections are supplemented by the scattered sound rays. The reflection is off a vertical wall and adjacent soffit.

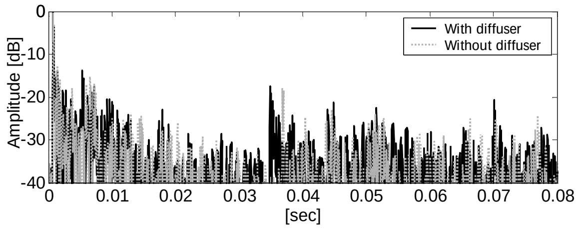


Figure 4. Part of energy distribution of the left channel measured at position A1 with and without the diffuser

Figure 5 shows the early impulse responses for position D3 both with and without a diffuser. The pattern of the reflections is different in both cases; when diffusers are installed, the amplitude of the first reflection decreases and the density of reflections increases.

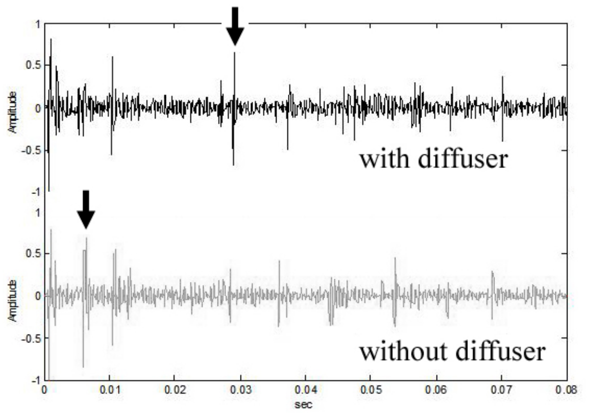


Figure 5. Impulse responses measured and Δt_1 positions at position D3 for the both conditions

3 Subjective preference tests

3.1 Experiment 1

3.1.1 Procedure

The previous studies on the effects of scattered sound in a concert hall showed T_{sub} and *IACC* were useful indicators for evaluating a scattered sound field [10]. From the objective measurements, when diffusers were installed, T_{sub} at almost all the seats decreased, whereas both $1\text{-}IACC_{E3}$ and $1\text{-}IACC_{L3}$ increased at front and side stalls, and decreased at rear stalls. Thus the subjective preference test was carried out to determine which variation of diffuser parameters chiefly affects subjective evaluation.

Six seats of the total of 15 seats in the model were selected for auditory tests using the variation trend of $1\text{-}IACC_{E3}$, because the early part ($1\text{-}IACC_{E3}$) showed larger variation than the late part ($1\text{-}IACC_{L3}$) as shown in Figure 3(d). Three of the seats (A1, A3, and B2) in which $1\text{-}IACC_{E3}$ mainly increased in scattered sound were selected as were three seats (D3, E2 and E3) in which $1\text{-}IACC_{E3}$ mainly decreased. Thus a total of 12 impulse responses at 6 seats − with and without diffuser − were used for the auditory test.

The test was performed using the stereo dipole technique with two loud speakers in an anechoic chamber, and the scale value as auditory preference was calculated by applying the method of paired comparative judgment (Thurstone's case V) [11]. Each subject was asked of which of two sounds he/she prefers. The subjects consisted of senior students of music at the university, because they were likely to have had experience making judgments about sound quality. The music source for the test was a violin motif of 4sec because its main frequency component is 1 to 2kHz.

A total of 66 sound pairs were randomly presented to the subjects. Experiment 1 was intended to determine what mainly causes the variation of auditory preference, the difference of the diffuser condition or the seats.

3.1.2 Results

A total of 20 subjects participated to the test, but only 17 subjects were passed the consistency test. Also 17 subjects showed significant agreement ($p<0.01$), in spite of a low coefficient of agreement ($u=0.06$). Figure 6 shows the scale values (S.V.) of 12 sources at 6 seats in two different conditions.

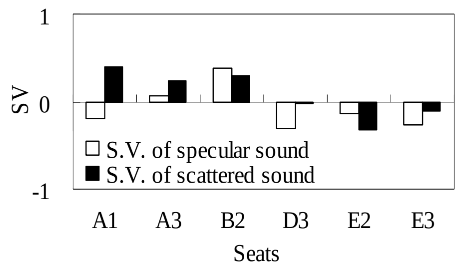
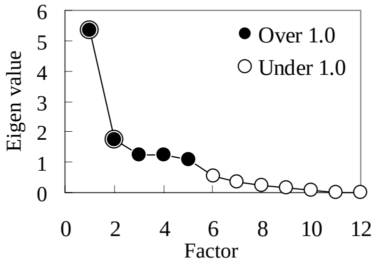


Figure 6. The scale values at 6 positions with the diffuser (scattered sound) and without (specular sound)

The scale values at positions A1, A3, D3 and E3 increased when the scattered sound was presented, and decreased at positions B2 and E2. But in the case of scattered sound, three seats of A1, A3 and B2 showed still high scale values regardless of the auditory preference of specular sound field. By contrast, three seats of D3, E2 and E3 showed still low scale values.



Subject	Fact. 1	Fact. 2
MY	0.67	0.09
LM	-0.74	0.55
SJ	0.84	0.11
MJ	0.85	-0.31
JH	0.81	0.33
YS	-0.93	0.18
JN	0.78	0.31
KS	0.94	0.18
BL	0.94	-0.12
YJ	0.72	0.05
JW	0.08	0.39
SM	-0.01	0.70
BM	-0.17	0.67
JM	0.28	0.60
YM	-0.30	0.81
KJ	0.58	0.64
SK*	-0.36	0.09

Figure 7. (Above) Eigenvalues of component factors; (Right) Two groups selected by Factor 1 and 2

* Although subject SK showed a high component value with Factor 1, the pattern of scale values was more similar to Factor 2.

The authors tried to find a correlation between the measured scale values and other orthogonal factors, but the pattern of averaged scale values differed from that of the scale value of each subject due to a low coefficient of agreement. Thus, there was a need to divide all subjects into several groups of different characteristic by applying factor analysis.

Factor analysis with the scale value of each subject gave five eigenvalues over 1.0, using the method of principal component analysis as shown in Figure 7. However, of the five, only factor 1 was markedly different. Thus, the other four factors were regarded as one for the purpose of grouping. As a result, all subjects were separated into two groups; group 1 had 10 subjects (u=0.12) and group 2 had 7 subjects (u=0.06).

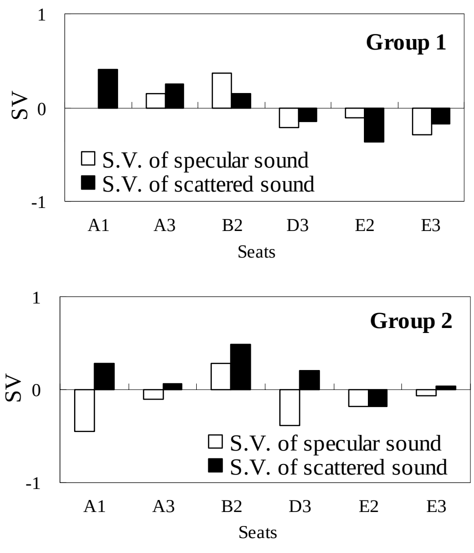


Figure 8. The scale values of each group without and with diffuser: (Left) Group 1, (Right) Group 2

Figure 8 shows the scale values of each group. The subjects in group 1 clearly preferred to the scattered sound field of A1, A3, and B2 over that of D2, E2, and E3. The subjects in group 2, however, showed a different pattern of scale value. Consistently, they preferred the scattered sound field to the specular one except for E2. The sums of the scale values of both groups increased when the diffuser were installed.

Table 3 shows the correlations between the four orthogonal factors and the scale values of each group. It can be known that the scale values of group 1 highly correlated with *LL*, T_{sub} and *1-IACC*$_{E3}$. However, group 2 shows low correlations with the orthogonal factors.

Table 3. Correlations between the four orthogonal parameters and the scale values

Correlation Coefficient	*LL*	Δt_1	T_{sub}	*1-IACC*$_{E3}$	*1-IACC*$_{L3}$
S.V.$_{\text{All subjects}}$	0.43	-0.13	0.69	-0.50	0.52
S.V.$_{\text{Group 1}}$	**0.74**	-0.06	**0.85**	**-0.70**	0.41
S.V.$_{\text{Group 2}}$	-0.41	-0.18	-0.05	0.20	0.39

3.2 Experiment 2

3.2.1 Procedure

Experiment 2 was carried out to verify the preferred positions revealed in Experiment 1. In Experiment 1, the sound fields of different seats were compared with each other. Thus, the result of Experiment 1 includes not only the effects of a diffuser, but also the effects of seat position.

To avoid a comparison between sound fields of different seats as experienced in Experiment 1, only two sound fields (with and without diffuser) at the same position were compared. By using sounds of all fifteen seats with two different conditions (A: with diffuser, B: without diffuser), A-B and B-A pairs at each seat were prepared. A two-alternative forced choice procedure was used. Other details were the same as in the previous experiment.

The same 20 subjects who participated in the previous test also participated in Experiment 2.

3.2.2 Results

Figure 9 shows the proportions of preference of auditory preference for the scattered sound field at all seats. All seats adjacent to the lateral wall (A3, B3, C3, D3 and E3) showed high proportions of preference. Also, A1 (the center of the front stalls) and E1 (the center of the rear stalls) showed high proportions of preference. Thus, the scattered sounds at these seats are better than the specular sounds there. But the seats at the center of the middle stalls (A2, C2, D2 and E2) showed low proportions of preference for the scattered sound. The results suggest that the wall diffusers improve the auditory preference in an area around them.

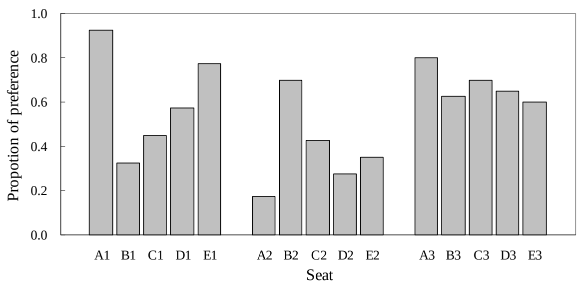


Figure 9. The proportions of preference of scattered sound fields at all 15 positions

The proportions of preference can be compared with the data from Experiment 1: The scale values measured in Experiment 1 include the comparison of distance difference, whereas the proportions of preference measured in Experiment 2 consider only variation at fixed positions. The positions A1, A3 and B2 are preferred in both Experiments 1 and 2 when diffusers are installed.

4 Discussion and conclusions

This study has investigated the effects of the diffusers through the measurements in 1:10 scale model and the subjective preference tests.

In Experiment 1, Group 1's responses showed high correlation with *LL*, T_{sub} and $1\text{-}IACC_{E3}$, whereas group 2 showed lower correlation with them. This shows that subjects in group 1 had definite criteria for sound evaluation. However, all the subjects equally perceived the variation of the sound field by the diffusion, despite of the dissimilarity of sensitivity between the two groups.

The results of objective measurements showed that the variance range of $1\text{-}IACC_{E3}$ was larger than that of $1\text{-}IACC_{L3}$ according to the diffuser, which means that factor responds sensitively to changes in condition.

The following effects of diffuser installation were found from the subjective and objective measurements:

(1) The first reflection (Δt_1) with maximum amplitude is delayed in rear seat positions. The bunch of early reflections in the impulse response was observed due to the scattered reflections either reflected by the wall or soffit closed to the proscenium first. Although Δt_1 was changed by the diffuser, subjects did not perceive the changing of Δt_1.

(2) *LL* decreased up to 2.6dB. T_{sub} decreased up to 0.08sec within *JND* (10%). Subjects perceived *LL* and T_{sub} as a major component of the scattered sound field.

(3) Both the values of $1\text{-}IACC_{E3}$ and $1\text{-}IACC_{L3}$ increase at the front and side seats near the source when diffusers are installed.

(4) There is an effective area or path of the wall diffuser on auditory preference. A lateral wall diffuser can improve the auditory preference in the front and the sides of stalls.

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