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SUBJECTIVE EVALUATION OF ACOUSTICAL CHARACTERISTICS IN EACH SEAT OF A CONCERT HALL

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1 INTRODUCTION

As the demand for higher acoustical quality in concert halls has become much greater than before, the theoretical researches for the acoustical quality index and the evaluation methods of the concert hall's acoustical quality also have been undertaken more seriously. Following this trend, various types of acoustical parameters such as RT (Reverberation Time) have been used to create an optimum sound environment regarding the geometrical shape and the size of a hall. However, since not all these factors seriously affect the acoustical quality of the concert hall, it is necessary to extract the factors affecting the audience's subjective evaluation and to consider these factors in the early stages of the concert hall design process.

1.1 Backgrounds

Barron[1] revealed the correlation between the audience's subjective evaluations and some acoustical characteristics by conducting a questionnaire survey in eleven British halls; between the factors affecting 'Overall Impression' such as Reverberance, Envelopment and Intimacy and objective factors such as SPL (Sound Pressure Level) EDT (Early Decay Time), LF (Lateral Fraction) and RT. In addition, Barron[2] also suggested the importance of the EDT/RT values in relations to the acoustical characteristics in seventeen British halls.

Yamaguchi[3] analyzed the correlation coefficient between subjective evaluation and the acoustical parameters of a hall, as well as the differences in acoustical properties among the seats. Ando[4] found that the ACF (Auto-Correlation Function)/IACF (Inter-aural Cross-Correlation Function) factors related to the subjective evaluation and suggested LL (Listening Level), IACC (Inter-Aural Cross-Correlation), ITDG (Initial Time Delay Gap), and T_{sub} (Subsequent Reverberation Time) as the factors affecting the subjective evaluation. Hotehama *et al*. [5] found that the audience distinguished the sound sources located on the stage based on the differences of τ_{IACC}. Morimoto *et al*.[6] found that the spatial factor LEV (Listener Envelopment) increases as the sound energy from the audience's back rises, and that late reflected sound (that is, Reverberance) is more effective in enabling the audience to experience LEV than early reflected sound. Okano *et al*. [7] found that the variation of the acoustical parameters among different seats of a hall is larger than that among different halls.

1.2 Present study

In the present study, eight seats in the Seoul Arts Center (SAC) Concert Hall were selected according to different acoustical parameters including spatial and temporal factors. A questionnaire survey was conducted to evaluate the acoustical characteristics of each seat. The survey form and the analyzing method from Barron[1] were adopted to find the acoustical factors affecting the subjective evaluation of each seat and the useful factors for the acoustical design through analyzing the correlation coefficient between the measured acoustical parameters and the ACF/IACF factors. The correlation coefficients were drawn by analyzing the results of the subjective evaluation in a real hall, and the results of the preference test using recorded sound sources.

2 THE SEOUL ARTS CENTER CONCERT HALL

The Seoul Arts Center (SAC) Concert Hall was designed by Kim Suk Chul and Associates and completed in 1988. For the acoustics of the hall, Rob Harris (Arup Acoustics, UK) carried out a review of the acoustical design at the scheme stage. Jeff Charles (Bickerdike Allen Partners, UK) also provided some advice at this stage. The SAC Concert Hall is the principal concert hall for the city of Seoul.

The form of the hall is essentially fan-shaped. It has a maximum capacity of 2,596, seated at three levels. The principal dimensions are length, 42m, width, 33m and height, 14-15m, with an auditorium volume of 23,300m^3. The mid-frequency reverberation time is 1.9sec.

Figure 1. SAC Concert Hall

A distinctive feature of the SAC concert hall is the size of the stage. With an area of 270m^2 and an average width of 22m, the stage is large even by contemporary standards. From the concert halls listed in Beranek's book[8], the average stage area in older halls (Amsterdam Concertgebouw, Boston Symphony Hall and Vienna Musikvereinssaal) is 158m^2, whereas modern halls built after 1962 have an average area of around 200m^2. An area of 190m^2 is generally considered adequate for a 100-piece orchestra. No reflectors have been placed above the SAC stage leaving a clear distance of 14-15m to the ceiling.

The walls of the stage contain triangular diffusers, which are intended to contribute to sound diffusion and provide support for the musicians. The diffusers are constructed of wood veneer on 6mm plasterboard. Figure 2 shows the 8 points selected from the audience area to conduct this research.

To measure the acoustical parameters such as RT (unoccupied), EDT, D_{50} (Definition), C_{80} (Clarity), T_s (Center Time), IACC, BR (Bass Ratio), SPL (Sound Pressure Level), and LF, the sound source was located 3m backwards from the middle of the stage front and 1m to the right.

Sound sources having the same length were recorded and played by CD. Among 32 points, 8 receiving points having different temporal and spatial characteristics (such as 1-IACC and LF) were selected. Table 1 shows the acoustical characteristics of these 8 points.

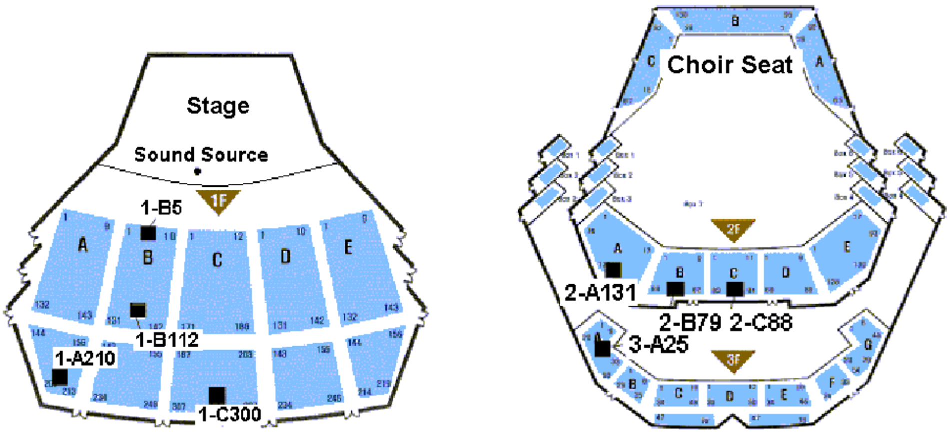

Figure 2. Locations of receivers and the sound source.

Table 1. Acoustical characteristics in each seat of the SAC concert hall

	1-B5	1-B112	1-A210	1-C300	2-A131	2-B79	2-C88	3-A25
RT (sec)	2.02	2.05	2.00	2.05	2.06	2.11	2.07	2.20
EDT (sec)	1.77	1.98	1.53	1.80	2.36	1.92	2.35	2.21
C80 (dB)	2.3	-0.4	1.0	0.1	-0.3	-0.6	-0.4	-3.2
Ts (ms)	93	133	107	127	143	135	147	167
BR	1.01	0.99	0.93	1.01	0.96	1.08	1.02	1.07
ITDG (ms)	35	32	11	9	34	34	34	22
SPL (dB)	88	89	86.5	82	88.5	86	87	84
d* (m)	6.7	15.0	23.9	21.4	25.4	25.7	25.8	26.2
LF	0.28	0.25	0.20	0.20	0.20	0.18	0.16	0.16

*d: the distance between the sound source and the receiving point

3 QUESTIONNAIRE SURVEY

3.1 Sound Source

The first questionnaire survey was conducted during the musical performance of a Ukrainian orchestra. During the first half of the performance, the prologue of ‘Le Mariage de Figaro’ and Mozart’s Symphony No. 41 ‘Jupiter’ were played. After the intermission, Beethoven’s piano concerto No. 5 ‘Emperor’ was played.

In the second questionnaire survey, Webber’s cello solo and a soprano solo composed by Sung-Ki Kim were played for the subjects using the omni-directional loud speaker on the stage.

3.2 Subjects

Eight subjects who were aged in their 20s participated in the first questionnaire survey, and 22 subjects (including 5 professional musicians plus 17 postgraduate students ranging in age from their 20s to 40s) participated in the second questionnaire survey.

3.3 Survey Method

Two questionnaire surveys were undertaken, and the first questionnaire survey consisted of two steps. In the first step of the first questionnaire survey, the survey was conducted during the rehearsal of the Ukrainian orchestra in the concert hall of SAC. In the survey, 8 subjects evaluated the acoustical characteristics of the 8 selected seats while the rest of the seats were unoccupied. The second step of the first questionnaire survey was conducted during the main performance as each subject evaluated two different seats before and after the intermission while the rest of the seats were unoccupied.

The second questionnaire survey was conducted under unoccupied conditions, and 22 subjects evaluated 8 seats by changing seats while the sound source has played to compare the 8 seats with each other.

The survey form created by Barron[1] in the subjective evaluation of British symphony halls was used in this research.

3.4 Results and Analysis

First, the audience responses for the three sound sources (Orchestra, Cello, Soprano) were analyzed by ANOVA. As a result, the P values for the three sources were the same at 0.58. Since there were no significant differences, the statistical analysis was undertaken by averaging the audience responses for each sound source. In the second questionnaire survey, the subjects were divided into two groups (5 professional musicians and 17 postgraduate students), and the survey results were compared. There were no significant differences between the two groups.

Table 2 contains the correlation coefficients analyzed by using the questionnaire survey results of the orchestra, cello and soprano. Bold characters signify P<0.05. As shown in Table 2, Reverberance, Envelopment and Intimacy have a high correlation with 'Overall Impression', which is the item of relative ascendancy for each seat. In particularly, the correlation coefficient of ENV was the highest at 0.85 (P<0.01). Thus, it can be said that, of these three items, audiences are most strongly influenced by the Envelopment.

Table 2. Correlation matrix between questionnaire scales

	CLA	REV	ENV	INT	LOUD	TRE	BASS	BACK	OVE
CLA	1.0								
REV	0.22	1.0							
ENV	0.47	**0.63***	1.0						
INT	**0.76***	0.41	**0.78***	1.0					
LOUD	0.47	-0.14	-0.24	0.38	1.0				
TRE	0.61	-0.03	0.33	0.36	**0.72***	1.0			
BASS	0.36	0.20	0.42	0.44	0.55	0.48	1.0		
BACK	0.18	0.24	0.37	0.21	0.05	0.26	0.49	1.0	
OVE	0.26	**0.59***	**0.85***	**0.67***	0.17	0.18	0.46	0.41	1.0

*P<0.01

(CLA = Clarity; REV = Reverberance; ENV = Envelopment; INT = Intimacy; LOUD = Loudness; TRE = Treble balance; BASS = Bass Balance; BACK = Background noise; OVE = Overall Impression)

To analyze the correlation coefficient between the surveyed items and measured acoustic parameters, a multiple regression analysis was undertaken by combining the first questionnaire survey of 8 subjects and the second questionnaire survey of 22 subjects.

As dependent variables for the multiple regression analysis, the responses for the three sound sources (orchestra, cello, and soprano solo) in each seat were used. Ten acoustic parameters (RT, EDT, ITDG, T_S, LF, BR, D_{50}, C_{80}, SPL, 1-IACC) were used as independent variables. To avoid the effects of multicollinearity, the D_{50}, 1-IACC, BR, ITDG, T_S, which correlated less with the dependent variable ('Overall Impression'), were eliminated from the independent variables.

Formula (3.1) is the result of the multiple regression analysis between the survey results of each seat and the acoustical parameters, and this formula has a significance level of $P<0.05$.

$$y = 0.272x_1 - 27.80x_2 - 1.70x_3 - 0.10x_4 - 18.57x_5 + 40.85 \tag{3.1}$$

Table 3. Coefficients

	T-value	Significance
(Constant)	1.93	0.07
RT	**-2.41***	**0.03**
EDT	-1.86	0.08
C_{80}	-0.96	0.35
LF	-1.94	0.07
SPL	**3.53***	**0.00**

*P<0.05

The acoustical parameters having a high correlation with 'Overall Impression' are SPL and RT. ITDG could also be an influential factor on the 'Overall Impression' since the correlation coefficient between SPL and ITDG is 0.72.

The sound source recorded by the dummy head was analyzed for ACF/IACF factors which contain the parameters (see Table 4) suggested by Ando et al.[9] To analyze the parameters, the prologue of 'Le Mariage de Figaro' by Mozart was used as the orchestral sound source.

Table 4. ACF/IACF factors

Symbols	Descriptions
$\Phi(0)$	Energy represented at the origin of the delay (dB)
ϕ_1	Amplitude of the first peak
SPL	Sound Pressure Level
τ_e	Effective duration of the envelope of the normalized ACF (ms)
τ_1	Delay time of the first peak (ms)
IACC	Magnitude of the inter-aural cross-correlation
τ_{IACC}	Inter-aural delay time at which the IACC is defined (ms)
W_{IACC}	Width of the IACC at the τ_{IACC}

To find out whether other parameters except loudness at the different positions affect the judgment of the acoustics in each seat, among the influential factors SPL was fixed and the others were analyzed as variables. To avoid multicollinearity, among the ACF/IACF factors $\Phi(0)$, τ_e, 1-IACC, and τ_{IACC} were used as the independent variables. 'Overall Impression' was used as the dependent variable.

The results of the multiple regression analysis show that τ_{IACC}, 1-IACC, and $\Phi(0)$ are highly correlated with 'Overall Impression', as shown in Formula (3.2). The details of the factors are shown in Table 5. If τ_{IACC}, the factor related to directional characteristics, reaches 0, the audience can hear a balanced sound by experiencing the sound coming from the front. The results also show that the 'Overall Impression' scale shows a higher value as the τ_{IACC} reaches 0. Hotehama *et al.*[5] found that τ_{IACC} is the most influential in affecting dissimilarity judgment when the sound source is located on the stage and the audience evaluates the sound in the same seat.

$$y = 17.71x_1 + 17.01x_2 + 0.273x_3 - 11.632 \quad (3.2)$$

Table 5. Coefficients

	T-value	**Significance**
(Constant)	-2.32*	0.03
x_1 = τ_{IACC}	5.10*	0.00
x_2 = 1 - IACC	4.16*	0.00
x_3 = $\Phi(0)$	2.87*	0.01

*P<0.05

4 SUBJECTIVE PREFERENCE TEST

4.1 Sound source

The sound source was part of the prologue of 'Le Mariage de Figaro' by Mozart, which is similar to Motif B[10] whose τ_e is 32ms.

4.2 Subjects

The age of 20 subjects varied from their 20's to 40's.

4.3 Methods

The sound samples recorded at the eight seats were compared to each other in the subjective preference test. A total of twenty-eight combination pairs of sound samples were judged by the pair comparison method. There was a 1 sec inter-stimulus interval between pairs of the 9-second sound samples, and the subjects reported their preference after listening to each pair. After presenting each pair of sound samples, it was asked, 'Which sound sample do you prefer?' The sound samples were randomly presented and each pair was repeated twice.

Kendall's Coefficient Consistency, K, was calculated to verify the consistency of the response pattern. To obtain a 95% significance level of normal distribution, the subjects whose K ranged from 0 to 0.52 were only selected for analysis.

4.4 Results and Analysis

The test scores at each seat were obtained from the subjective preference test through headphones. As shown in Table 6, it was found that seat 1B5 was the most preferred, and seat 2C88 was the least preferred on the 7-point scale score.

Table 6. Subjective preference test score

	1B5	1B112	1A210	1C300	2A131	2B79	2C88	3A25
Score	5.41	4.47	3.76	3.12	4.53	2.76	1.53	2.35

Formula (4.1) shows the results of the multiple regression analysis. According to Table 7, the effect of LF was the highest. RT and EDT were also related to preference.

$$y = 59.59x_1 + 41.06x_2 + 2.78x_3 - 0.16x_4 + 2.83x_5 - 80.33 \qquad (4.1)$$

Table 7. Coefficients

	T-value	Significance
(Constant)	-80.33*	0.01
x_1 = **LF**	59.59*	0.00
x_2 = **RT**	15.91*	0.01
x_3 = **EDT**	1.20*	0.02

*P<0.05

According to the correlation between the ACF/IACF factors and the average of the preference test scores, the correlation coefficients of τ_{IACC} and SPL were the highest (r=0.72 and 0.68, respectively, p<0.05). This result confirms that the τ_{IACC} is the factor affecting 'Overall Impression' as shown in formula 3.2 and Table 5.

5 CONCLUSION

The questionnaire survey was conducted for the seats having just noticeable differences (or difference limen[11]) in acoustical characteristics in order to investigate the correlation between the survey results and the acoustical parameters. As a result, it was revealed that REV, ENV and INT have high correlations (ENV is the highest) with the subjective evaluation as previously investigated.[1] Among the acoustical parameters, SPL, RT, ITDG and LF had a high correlation with 'Overall Impression' in the multiple regression analysis.[2,12,13]

In the multiple regression analysis of the ACF/IACF parameters in a real hall, τ_{IACC}, 1-IACC, and $\Phi(0)$ showed high correlations with 'Overall Impression'. Moreover, the preference test scores for reproduced sounds highly correlated with τ_{IACC}. This result validates that τ_{IACC} is the factor affecting the audience subjective evaluation for both a real hall and a recording.

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