Journal of Sound and Vibration (2000) **232**(1), 149–155
doi:10.1006/jsvi.1999.2690, available online at http://www.idealibrary.com on IDEAL®

REVERBERANCE OF AN EXISTING HALL IN RELATION TO BOTH SUBSEQUENT REVERBERATION TIME AND *SPL*

S. HASE†, A. TAKATSU‡, S. SATO, H. SAKAI AND Y. ANDO

Graduate School of Science and Technology, Kobe University, Kobe 657-8501, *Japan*

(*Accepted* 30 *June* 1999)

The reverberance of sound fields was evaluated by psychological tests in a multi-purpose hall with 400 seats. Both the subsequent reverberation time (T_{sub}) and sound pressure level (*SPL*) were changed, and the scale values of reverberance for both the music and speech signals were obtained by using the paired comparison method. This study found that T_{sub} and *SPL* have an independent influence on the scale value of reverberance. The reverberance increases when both T_{sub} and *SPL* are increased.

1. INTRODUCTION

The subjective preference of sound fields in a hall can be described by four orthogonal physical factors: listening level, delay time of early reflection, subsequent reverberation time (T_{sub}), and *IACC* [1]. T_{sub} is defined as a subsequent reverberation time (s), that is, a decay time in which amplitude decrease, by 60 dB after the early reflections. Practically, T_{20} or T_{30} can be used. This was shown to be true for sound fields in an existing hall [2]. The relationship between reverberance and the four orthogonal physical factors, however, has not been investigated. In this study, psychological tests relating to the reverberance of sound fields were conducted. Two orthogonal factors, T_{sub} and *SPL*, were changed, and the scale values of reverberance for both the music and speech signals were obtained by using the paired comparison method. The relationship between reverberance and these two physical factors was examined.

2. PROCEDURES

For the experiment, a hall in Kobe (ORBIS HALL [3]) with 400 seats was used (see Figure 1). Music and speech were used as a source signal (see Table 1). The

†Also, Theater Design Laboratory Co., 2-13-26 Makinohonmachi 573-1144 Hirakata, Osaka, Japan.
‡Also, Showa Sekkei Co., 1-2-1-800 Benten, Minato, Osaka, 552-0007 Japan.

0022-460X/00/160149 + 07 $35.00/0

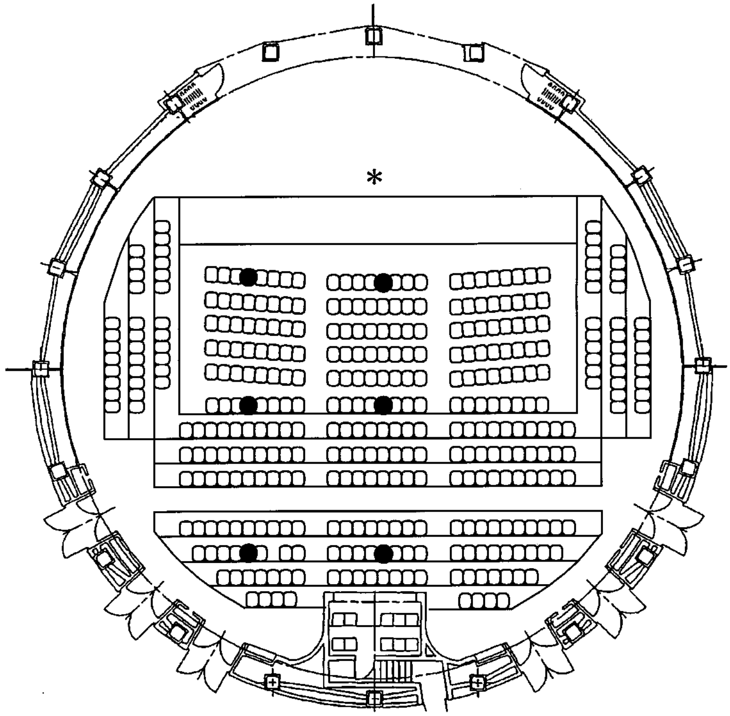

Figure 1. Plan of the existing hall (ORBIS HALL, Kobe): *, Sound source; ●, listener's location (6 positions).

TABLE 1

Sound signals used in experiment

Source signal	Title	$(\tau_e)_{min}$ (ms)
Music (9 s)	Marriage of Figaro Overture (by Mozart)	59
Speech (9 s)	Female speech (Japanese)	11

minimum values of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function (*ACF*), with the integration interval $2T = 2{\cdot}0$ s, of both the music and speech signals were, respectively, 59 and 11 ms. The spectrum levels of the sound signals after passing through the A-weighting network are listed in Table 2. Paired-comparison tests were conducted as the subsequent reverberation time T_{sub} and the sound pressure level (*SPL*) were changed. The subsequent reverberation time T_{sub} was adjusted by a hybrid system, consisting of an electroacoustic system and a small reverberation chamber, which reproduced fine structured reflections in the decay, as shown in Figure 2. Sound signals were reproduced from an omni-directional dodecahedron loudspeaker located on the stage (1·35 m above the stage floor, and 2·20 m from the front edge of the stage) and

TABLE 2

Octave band spectrum level in dB *of the sound signals used in experiments through an A-weighting network*

	Spectrum level (dB)					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Music	− 19·7	− 11·5	− 4·2	0·0	− 1·6	− 7·4
Speech	− 26·2	− 3·8	− 1·0	0·0	− 2·9	− 8·8

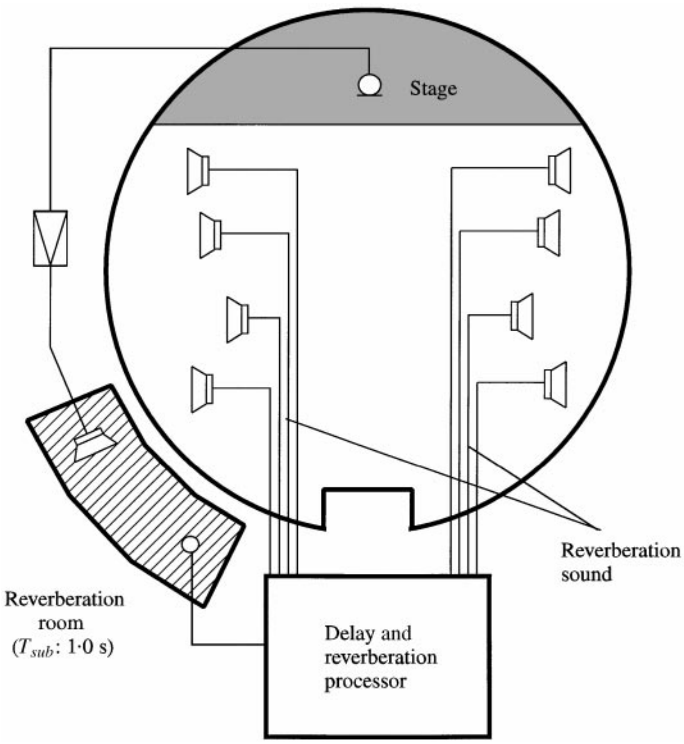

Figure 2. Block diagram of a hybrid reverberation system.

picked up by a microphone on the stage (0·50 m from the loudspeaker and 1·10 m above the stage floor). The signals radiated from the loudspeakers distributed near the ceiling were delivered through the hybrid reverberator and were superposed on the reverberant sound in the hall. Values of T_{sub} measured at the specified positions shown in Figure 1 are listed in Table 3. Because there was little difference in the measured values of T_{sub} among seats, the measured values at the six seat positions were averaged. The frequency characteristics of measured T_{sub} without

TABLE 3

Range of measured subsequent reverberation times of six seats

	T_{sub} (s)					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Off	$1·02 \pm 0·29$	$0·87 \pm 0·15$	$0·91 \pm 0·05$	$1·01 \pm 0·14$	$1·15 \pm 0·12$	$1·14 \pm 0·11$
On	$2·06 \pm 0·10$	$1·19 \pm 0·17$	$0·92 \pm 0·07$	$1·25 \pm 0·18$	$1·70 \pm 0·10$	$1·40 \pm 0·09$

Note: Off: without the reverberation system: On: with the reverberation system.

TABLE 4

Conditions of the experiment

Factors	1	2	3	4
SPL	80 dB	80 dB	70 dB	70 dB
T^*_{sub}	Off	On	Off	On

*Off: without the reverberation system; On: with the reverberation system (Table 3).

reverberation was almost flat around 1·0 s. When the reverberation was superposed, on the other hand, the subsequent reverberation time was increased to more than 1·25 s at higher frequencies, and further, it rose up to 2·06 s at 125 Hz octave band.

Conditions of the experiment are listed in Table 4. Twenty-one subjects were divided into six groups and seated at the specified positions (see Figure 1). To exclude the effects of other orthogonal physical factors such as visual and tactile senses on judgments, the subjects were asked to remain in their seats and judge which of the two sound fields they perceived to have more reverberance. The test consisted of 6 pairs ($N(N-1)/2$, $N=4$) of stimuli, in total. The signal duration of each stimulus was 9 s, and the silent interval between the stimuli was 1 s. In order to avoid a sudden termination of the sound signal, the last 2 s of the sound signal were faded out. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order. In order to obtain enough data, a contiguous set of three or four seats was used in a single test session. The session was repeated three times, with subjects changing seats between sessions, and 21 subjects in total responded at each set of seats. It took about 30 min.

3. RESULTS AND DISCUSSION

The scale value of reverberance was obtained by applying a modification of the Thurstone method [4].

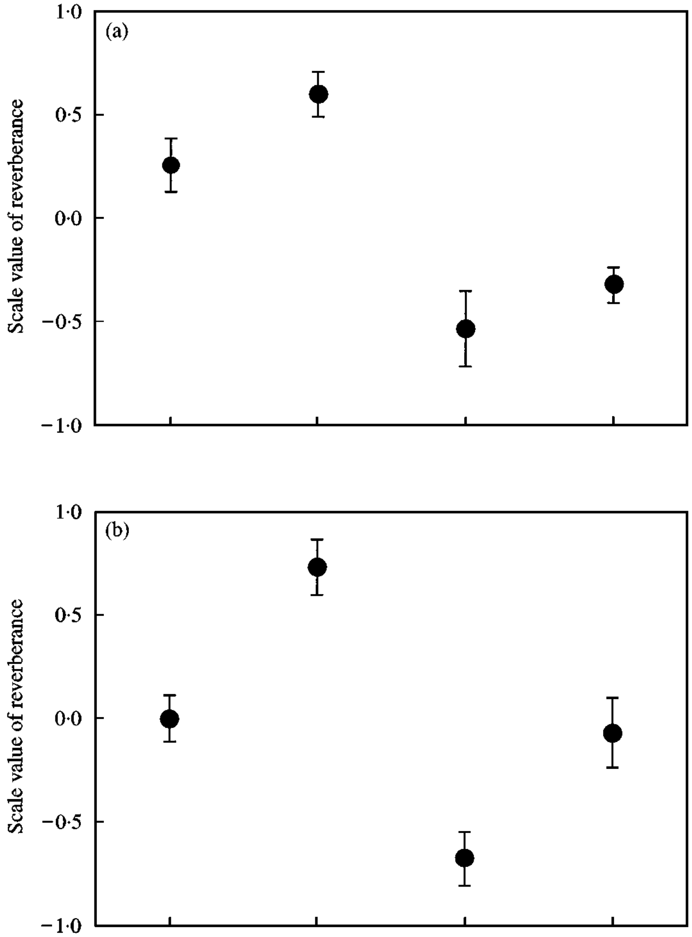

Figure 3. Average scale values of reverberance (six seats) with 95% reliability. (a) Music; (b) speech: *On, with the reverberation system; Off, without the reverberation system.

Because there was no significant difference in the scale values of reverberance among the seats, the scale values of the six groups of seats were averaged. As shown in Figure 3, the scale values of reverberance for the sets of both sound signals increased as SPL or T_{sub} increased. As shown in Table 5, the results of the analysis of variance for the scale values of reverberance indicate that the factors SPL and T_{sub} are significant ($p < 0{\cdot}01$). Effects of the interaction between SPL and T_{sub} are not significant. Results reveal that T_{sub} and SPL contribute to the scale value of reverberance independently, so that

$$s(\text{Rev}) \approx f(SPL) + f(T_{sub}) \approx a_1 X_1^{3/2} + a_2 X_2^{5/2}, \tag{1}$$

where $X_1 = SPL$ (dB) and $X_2 = \log_{10}[T_{sub}/c(\tau_e)_{min}]$. Coefficients obtained by multiple regression are $a_1 \approx 0{\cdot}007$, $a_2 \approx 1{\cdot}95$, and $c \approx 6$. This equation can apply to the range of $T_{sub} \geqslant 0{\cdot}07$ (s) for speech, and $T_{sub} \geqslant 0{\cdot}36$ (s) for music. The values of the subsequent reverberation time are determined from the averaged value of

TABLE 5

Results of the analysis of variance for the scale values of reverberance

Facotrs	Sum of square	DF	Mean square	F-ratio	p-value
Music					
LL	4·43	1	4·43	312·03	<0·01
T_{sub}	0·47	1	0·47	32·94	<0·01
Seat	0·00	5	0·00	0·00	1·00
LL and T_{sub}	0·03	1	1·83	1·83	0·23
Residual	0·07	5	0·01		
Speech					
LL	3·29	1	3·29	72·63	<0·01
T_{sub}	2·69	1	2·69	59·54	<0·01
Seat	0·00	5	0·00	0·00	1·00
LL and T_{sub}	0·02	1	0·02	0·48	0·52
Residual	0·23	5	0·05		

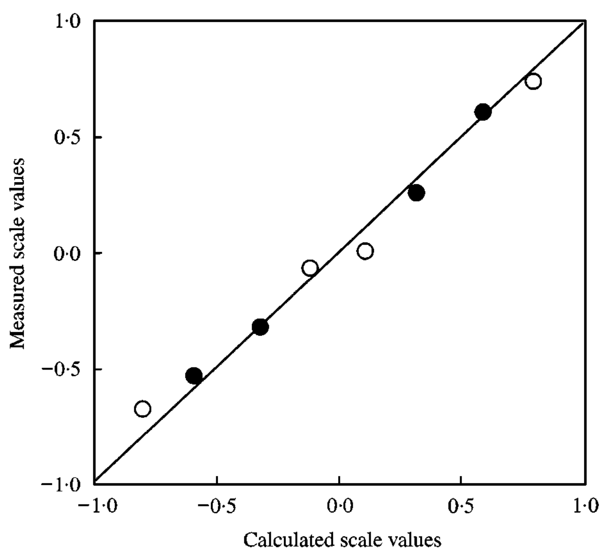

Figure 4. Relationship between the calculated scale values of reverberance by equation (1) and measured scale values of reverberance. The correlation coefficient, $r = 0{\cdot}99$ ($p < 0{\cdot}01$): ●, Music; ○, Speech.

the octave bands whose spectrum level exceeds − 6 dB. Figure 4 shows the relationship between the measured scale values of reverberance and scale values of reverberance calculated by equation (1). The correlation coefficient was 0·99 ($p < 0{\cdot}01$).

The effects of the *SPL* on reverberance may be related to the sensation level of reverberation decay, which means that the higher *SPL* could result in greater reverberance.

The preferred T_{sub} is calculated by the τ_e of the source signal [1]. It may be considered that reverberance is affected not only by the reverberation time obtained from the reverberation curve but also by the effective duration of the ACF τ_e of the source signal. In addition, sound sources with shorter τ_e values may contribute more to reverberance.

4. CONCLUSIONS

The relationship between the reverberance of the sound field and the two orthogonal physical factors, T_{sub} and SPL, was examined for the sound field in an existing hall. The results indicate that T_{sub} and SPL contribute to the scale value of reverberance independently for both music and speech sound signals. The scale value of reverberance increases independently as both the T_{sub} and the SPL increase.

REFERENCES

1. Y. Ando 1998 *Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners*. New York: AIP Press/Springer-Verlag.
2. S. Sato, Y. Mori and Y. Ando 1997 in *Music and Concert Hall Acoustics* (Y. Ando and D. Noson editors), London: Academic Press, chapter 12. One the subjective evaluation of source locations on the stage by listeners.
3. A. Takatsu, S. Hase, H. Sakai, S. Sato and Y. Ando 1999 *Journal of Sound and Vibibration* (*Special Issue on Opera House Acoustics*). Acoustical design and measurement of a circular hall, improving a spatial factor at each seat.
4. Y. Ando and P. K. Singh 1996 *Memoirs of the Graduate School of Science and Technology, Kobe University* 14A, 57–66. A simple method of calculating individual subjective responses by paried comparison tests.