Journal of Sound and Vibration (2000) **232**(1), 157–169
doi:10.1006/jsvi.1999.2691, available online at http://www.idealibrary.com on IDEAL®

INDIVIDUAL SUBJECTIVE PREFERENCE OF LISTENERS TO VOCAL MUSIC SOURCES IN RELATION TO THE SUBSEQUENT REVERBERATION TIME OF SOUND FIELDS

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(*Accepted* 30 *June* 1999)

The purpose of this study is to evaluate individual differences and intra-individual changes of subjective preference of simulated sound field judged by listeners in changing subsequent reverberation time T_{sub} using a vocal source. A great deal of effort has been made studying subjective preferences by using music or speech. Subjective preference tests were conducted by changing T_{sub}, which is one of the four orthogonal-objective parameters of sound field.

1. INTRODUCTION

It is well known that subjective preference evaluation of sound fields is accompanied by individual differences [1, 2]. Using results from subjective preference tests in relation to orthogonal parameters of sound fields, each listener can select his or her optimum seat in a given concert hall [3]. Psychological evaluations in relation to preference of sound fields have been considered by their global results as an average of many subjects and also for each subject [4, 5]. In order to clarify individual differences in subjective preference, intra-individual changes should be investigated. The variations of preference evaluations caused by aging, seasons, time (morning, evening or night), a certain period of time during the repetition of psychological tests, and so on, are considered. As a typical example, a person's hearing level may be affected by aging. In this study, the variation of preference evaluations during the repetition of psychological tests is applied to intra-individual changes.

In a previous study on intra-individual changes in *SPL* by using a music source [6], it was found that subjects with large α values (see later for the definition of α) have smaller intra-individual changes than subjects with small ones, and the range of the variation of preferable *SPL* is small.

Subjective preference evaluations for intra-individual changes are identified by two factors from subjective preference curves obtained from paired-comparison tests as well as their global case and individual differences. One factor is the value at the most preferred parameter, which coincides with the peak of the preference curves. The other is the sharpness of the curve, α, which is an index of the degree of preference; see equation (3). For a unit variation of a parameter, the scale value for a certain subject with a large α value changes more rapidly than that of other subjects with a small α. Procedures for obtaining these parameters are described in the next section.

For vocal music, which is one of the main components of performances in opera houses, this study evaluates listener's individual differences and intra-individual changes in subjective preference to various simulated sound fields. Subjective preference tests were conducted by changing subsequent reverberation time, T_{sub}, which is one of the four orthogonal parameters that describe subjective preference to sound fields. The value of T_{sub} is defined by the decay rate of the sound pressure level after arrival of the first reflection until -60 dB. For calculating scale values of tests, a simple method of calculating individual subjective preference was adopted [7].

2. EXPERIMENTAL METHOD

2.1. CHARACTERISTICS OF A SOUND SOURCE

The sound source used was an initial 6·0 s piece of a solo performance of a soprano single ("O mio babbino caro" from "Gianni Schicchi" composed by G. Puccini) recorded in an anechoic chamber. Values of τ_e, which is the effective duration of the normalized autocorrelation function (*ACF*), $\phi(\tau)$, of a short-time moving *ACF* or running *ACF* ($2T = 2{\cdot}0$ s with the interval of 100 ms) [8] for the initial 6·0 s part of the source reproduced in the listening semi-anechoic chamber, were calculated. The waveform and values of running τ_e are indicated in Figures 1(a) and (b) respectively. The short-time moving *ACF* was calculated in order to obtain the minimum of its running τ_e, which represents the most rapid movement of music, activating the left cerebral hemisphere [9]. As indicated in Figure 1(c), the running τ_e is practically obtained by calculating the decay rate extrapolated in the range from 0 dB, at the origin, to -5 dB. The 2·0 s duration corresponds to the psychological present [10] and the minimum duration of signals corresponds to response to any subjective attributes. The most preferred T_{sub} averaged for a number of listeners can be calculated by using the equation [11]

$$[T_{sub}]_p \approx 23(\tau_e)_{min}, \qquad (1)$$

where $(\tau_e)_{min}$ is the minimum value of τ_e for the source music. The calculation of global preferable subsequent reverberation time $[T_{sub}]_p$ is about 0·53 s, which is shorter than usual music sources but longer than that of speech signals.

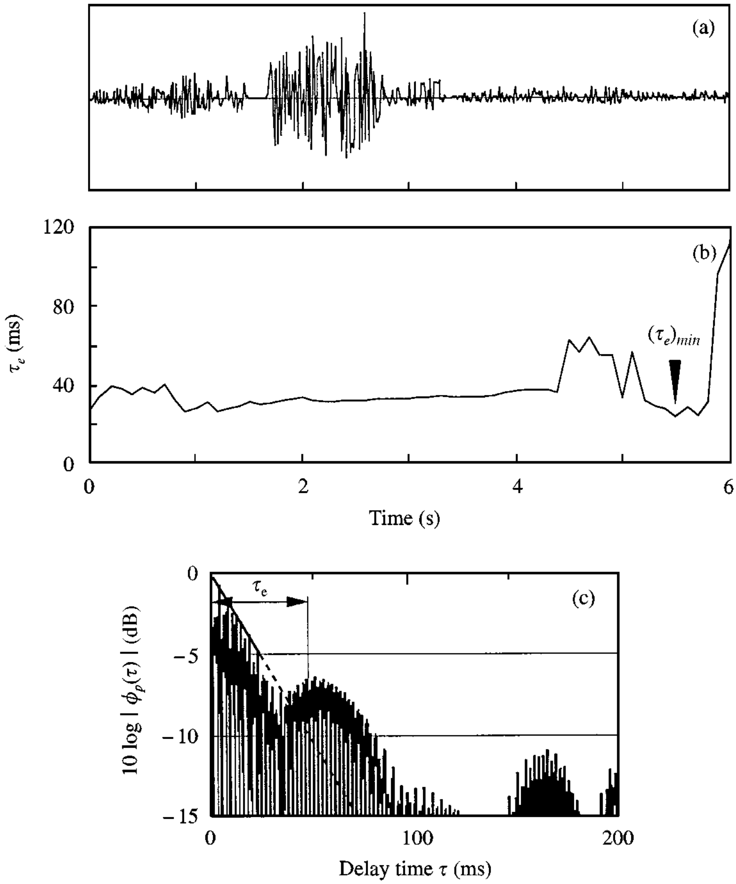

Figure 1. The effective duration τ_e of the running normalized autocorrelation function of the vocal source used in the tests. The integration interval, $2T$, is 2·0 s. The waveform of the vocal source reproduced in the listening-semi-anechoic room (a). The minimum value of τ_e, which is the most active part of the source containing important information and influencing subjective responses to the temporal criteria, is found to be about 23 ms (b). An example of determining the value of τ_e fitting 0 to -5 dB of the envelope (c).

2.2. PSYCHOLOGICAL EXPERIMENT

Paired-comparison tests were conducted in a semi-anechoic room (see Figure 2). With $[T_{sub}]_p$ taken to be about 0·53 s as mentioned above, the subsequent reverberation time T_{sub} of the sound field was changed from 0·1 to 1·6 s (see Table 1). The conditions of the other orthogonal parameters were fixed as indicated in Table 1. The initial time-delay gap between the direct sound and the first reflection, Δt_1, was fixed at 14 ms near to the most preferred value $[\Delta t_1]_p \approx (1 - \log_{10} A)$ $(\tau_e)_{min} \approx 16$ ms. The $IACC$ is near to unity because the two loudspeakers were set in front of the subjects. The total amplitude of reflections A is kept constant at 2·0. The duration of each stimulus presented to subjects was 6·0 s. The time interval between the two stimuli in a pair was 1·0 s and between each pair lasted 4·0 s. There are 10

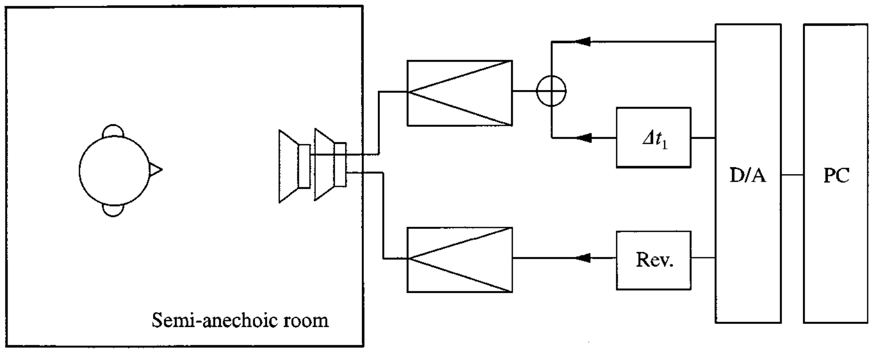

Figure 2. Experimental set-up of subjective preference tests controlling both the initial time delay gap between the direct sound and the first reflection, Δt_1, and the subsequent reverberation time, T_{sub}.

TABLE 1

Subsequent reverberation time T_{sub} values under fixed conditions of SPL, Δt_1 IACC and the total amplitude of reflections A

Factors varied or fixed		Value(s) of each factor				
T_{sub}	(s)	0·1	0·2	0·4	0·8	1·6
SPL	[dB(A)]			75·0 ± 0·2		
Δt_1	(ms)			14		
IACC				≈1·0		
A				≈2·0		

pairs in a series which are all the available pairs for five sound fields ($N(N-1)/2 = 10$, $N = 5$). A series of 20 paired-comparison tests were conducted on each subject. The number of subjects was eight (subjects A–H: seven males and one female; 21–26 years old). The stimuli were produced by two loudspeakers placed in front of the subjects in the listening room. The distance between a subject and the loudspeakers was 0·8 ± 0·01 m. One speaker provides a direct sound and the first reflection, and the other provides reverberation including some initial reflections. Subjects were required to select the most preferred sound field of the two they listened to.

2.3. CALCULATION OF THE SCALE VALUE

We used the subjective responses from each subject to calculate the scale values of preference for each sound field. The procedure for calculating scale values of preference is outlined in Table 2. The scores for each presented pair are obtained by giving scores of +1 and 0 corresponding to positive and negative judgments

TABLE 2

Example of obtaining scale values of sound fields calculated by equation (2) (*subject G*)

T_{sub} (s)	0·1	0·2	0·4	0·8	1·6	T_i	S_i
0·1	10	3	2	0	15	30	−0·501
0·2	17	10	1	0	18	46	−0·100
0·4	18	19	10	0	17	64	0·351
0·8	20	20	20	10	19	89	0·978
1·6	5	2	3	1	10	21	−0·727

respectively. For example, the score of the pair (0·4 s, 0·1 s) listed in Table 2 is 18. This result shows that the subject prefer the sound field with 0·4 s 18 times of 20 times to the sound field with 0·1 s. The ideal preference score comparing sound fields with same value of T_{sub} is 0·5 as "a tie" [12] and, thus, the scores of diagonal set in the table are 10 (against 20 times). The values of T_i represent the total score. The scale value of subjective preference for sound field i can be obtained by assuming a normal distribution of preference judgment [7]; i.e.,

$$S_i \approx \sqrt{2\pi}(2T_i - N)/2N. \tag{2}$$

Here N indicates the number of sound fields (= 5). This approximate equation is derived from case V of Thurstone's law of comparative judgment [13] and holds the linear domain of a normal ogive ($0{\cdot}05 < P < 0{\cdot}95$, P: probability judged). Each subject's most preferred value, $[T_{sub}]_{p,m}$, is obtained at the peak of the preference curves. The formula used for fitting scale values of preference is given by [11]

$$S \approx -\alpha |x|^{\beta}, \tag{3}$$

where

$$x = \log(T_{sub}/[T_{sub}]_p). \tag{4}$$

The value of $[T_{sub}]_p$ is obtained by equation (1). Weighting coefficient α indicates the sharpness of curve. If a subject has a large α value, the degree of preference decreases sharply as the value of T_{sub} is apart from the preferred value. The value of the weighting coefficient β may be found to be around three halves, in regard to subjective preference of sound fields [1, 11]. Weighting α can thus be obtained. The individual α value can be obtained from the average of preference score T_i in Table 2 for all series of tests and all subjects.

A test of goodness of fit to ensure the fitness of the model is adopted. The value of λ represents the poorness of the model ($0 < \lambda < 1$) and is defined by

$$\lambda = \sum_{(i,j)} |S_i - S_j|_{Poor} \Big/ \sum_{(i,j)} |S_i - S_j|, \quad 0 \leqslant \lambda \leqslant 1, \tag{5}$$

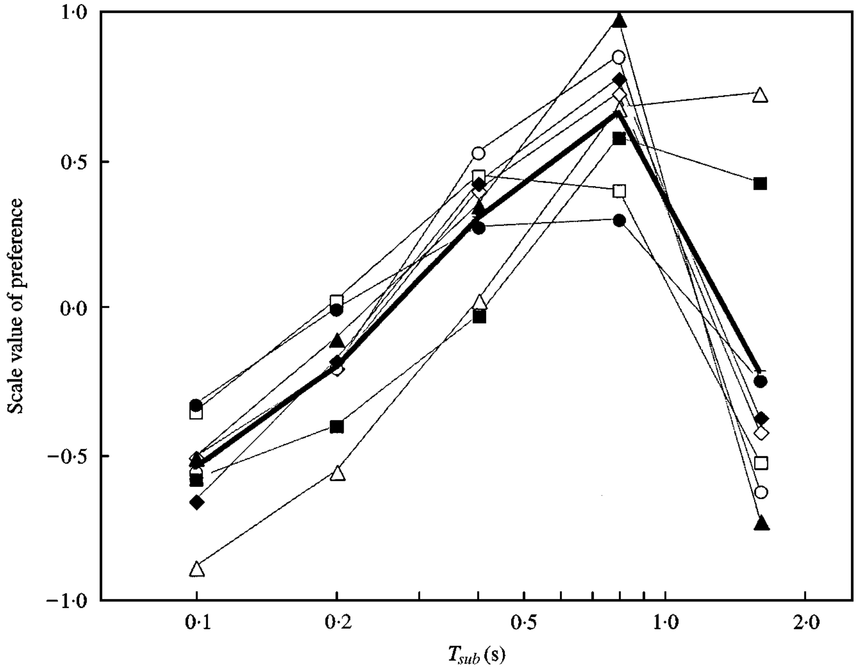

Figure 3. Scale values of preference for each subject as a function of T_{sub}. Different symbols indicate results from different subjects: ◇, ○, △, □, ◆, ●, ▲, and ■ for subjects A through H respectively. The bold line represents the averaged values.

where

$$|S_i - S_j|_{Poor} = S_j - S_i > 0, \quad \text{if } Y_i = 0, =0, \quad \text{if } Y_i = 1. \tag{6}$$

The value of λ corresponds to the average error of the scale value. This should be small enough: for example, less than 10%. The value of Y_i represents the score for each alternative judgment.

Another observation is that, when the poorness number is K, satisfying the condition expressed by upper part of equation (6), then the percentage of violations d is defined by

$$d = \frac{2K}{N(N-1)} \times 100. \tag{7}$$

3. RESULTS

3.1. INDIVIDUAL DIFFERENCES AND GLOBAL CASE

The measured results of the scale values of preference as the function of the T_{sub} for each subject and its global case are indicated in Figure 3. In this figure, different symbols represent the results from each subject, and the bold line

TABLE 3

Values of $[T_{sub}]_{p,m}$, α_s (for $T_{sub} < [T_{sub}]_{p,m}$) and α_l (for $T_{sub} > [T_{sub}]_{p,m}$) obtained for global and each subject

	Global	Subject							
		A	B	C	D	E	F	G	H
$[T_{sub}]_{p,m}$ (s)	0·78	0·81	0·69	1·22	0·55	0·74	0·59	0·81	1·07
α_s	1·53	1·53	2·02	1·61	1·38	1·86	0·97	1·87	1·40
α_l	5·24	7·65	7·09	1·69	3·27	6·19	2·12	11·04	4·08

TABLE 4

Result of analysis of variance (ANOVA). Individual differences are observed in $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ ($p < 0{\cdot}05$) and α_s ($p < 0{\cdot}01$)

Factor	F-ratio	p-value
$\log([T_{sub}]_{p,m}/[T_{sub}]_p)$	2·740	0·0285*
α_s	4·495	0·0022**
α_l	1·929	0·1054

Note: $*p < 0{\cdot}05$; $**p < 0{\cdot}01$.

represents the averaged value as the global result. As the sharpness of the curves are found to be different for each side of the preference curves' peaks, two values of α for both sides of the peak are considered as α_s for $T_{sub} < [T_{sub}]_{p,m}$ and α_l for $T_{sub} > [T_{sub}]_{p,m}$ in equation (3). The range of most preferred values of subsequent-reverberation time $[T_{sub}]_{p,m}$ obtained for all subjects in the tests was between 0·55 and 1·22 s. The largest value of α_s was 2·02 (subject B) and the smallest one was 0·97 (subject F). On the other hand, the largest value of α_l was 11·04 (subject G) and the smallest one was 1·69 (subject C). The values of α_l are always greater than those of α_s, for all subjects tested without exception. The experimental measurements of $[T_{sub}]_{p,m}$, α_s, and α_l for each subject as well as global results are listed in Table 3. The goodness of fit of this model for each subject, expressed using λ in equation (5) representing the poorness of the model for each subject, gives zero except for 0·04 for subject B. The values of d in equation (7) were also zero for all subjects except for 0·1 for subject B. These small values indicate that a consistent model is achieved for this test. Individual difference is found in $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ ($p < 0{\cdot}05$) and α_s ($p < 0{\cdot}01$) by use of analysis of variance (ANOVA), as shown in Table 4. The method of ANOVA is referred to in Appendix II. For example, subject B ($\alpha_s = 2{\cdot}02$ and $\alpha_l = 7{\cdot}09$) and subject G ($\alpha_s = 1{\cdot}87$ and $\alpha_l = 11{\cdot}04$) show a sharper preference curve than subject D ($\alpha_s = 1{\cdot}38$ and $\alpha_l = 3{\cdot}27$) and subject F ($\alpha_s = 0{\cdot}97$ and $\alpha_l = 2{\cdot}12$). In the global results obtained in the tests, $[T_{sub}]_{p,m}$ was 0·78 s, and values of α_s and α_l were 1·53, and 5·24 respectively. This means that for T_{sub} greater than the most preferred value, preference curves are sharper than those for T_{sub} less than the most preferred value.

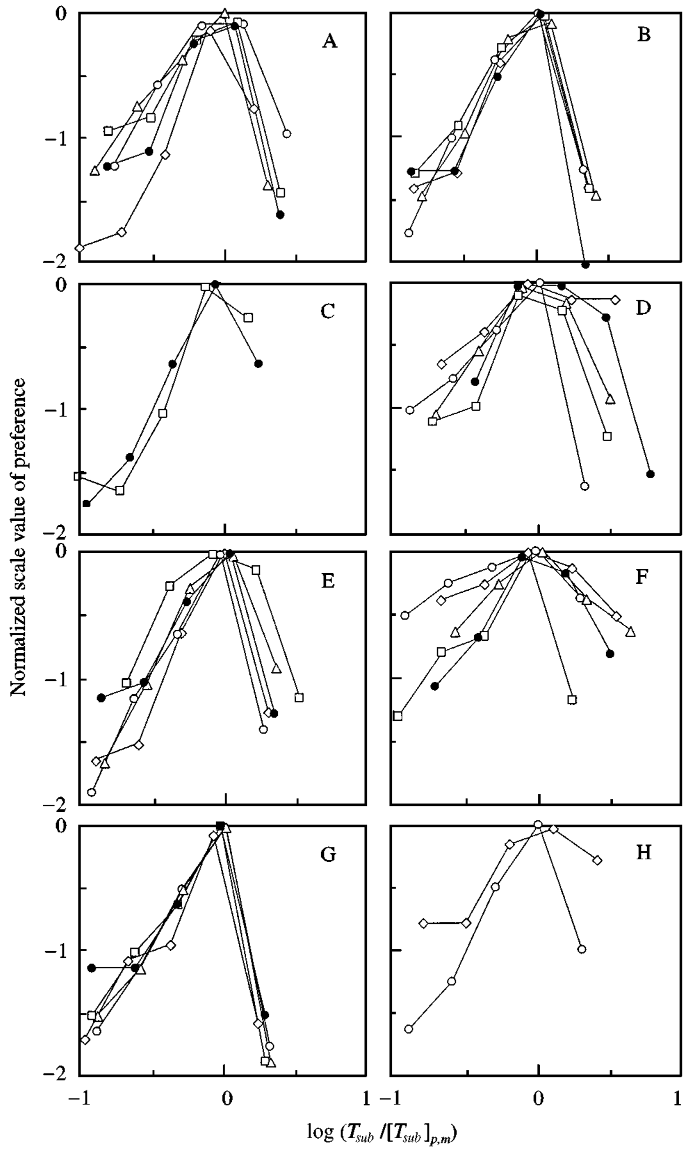

Figure 4. Individual scale values of preference obtained from every four series of each subject as a function of the normalized subsequent reverberation time. The peaks of the curves are shifted to the origin without any loss of information. Different symbols indicate values of a different series of tests: ◇, ○, △, □, and ●.

3.2. INTRA-INDIVIDUAL CHANGES

The measured results of intra-individual changes of subjective preference for each subject (A–H) are indicated in Figure 4. In this figure, different symbols represent the results in every four series of tests performed over three or four days. Each peak value of the preference curves is shifted to the origin without losing any information, because a scale value is a relative and a linear scale. For example,

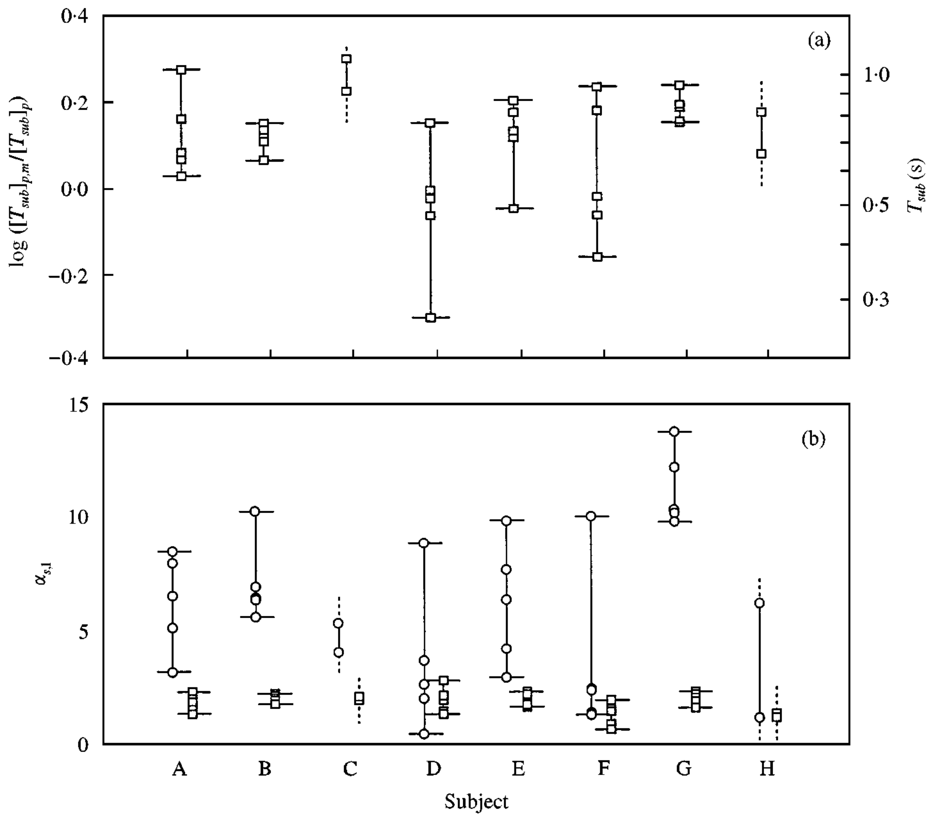

Figure 5. Intra-individual changes of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ (a); α_s (□) and α_l (○) for each subject (b). Broken lines show that preferred values are out of the range between 0·1 s and 1·6 s

curves of subjects B and G are almost the same, but those of subjects D and F are greatly changed over five sets of tests. There are only two curves of both subjects C and H, because the other three sets could not be obtained. The measured results of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, α_s, and α_l for each set are indicated in Figure 5. Subjects with large α values, like subjects B and G, have small intra-individual changes with respect to values of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$. Standard deviations of these factors obtained from each set of tests are listed in Table 5. The values of subjects C and H, with only two sets, are not listed. Subject B (0·033) and subject G (0·035) have the two smallest standard deviations of all subjects, and subject D (0·163) and subject F (0·168) have larger standard deviations. In relation to those of α_s and α_l, subject B (α_s: 0·16; α_l: 1·84) and subject G (α_s: 0·26; α_l: 1·68) have smaller standard deviations as well as the values of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$. On the other hand, subject D (α_s: 0·61; α_l: 3·21) and subject F (α_s: 0·55; α_l: 3·67) have larger standard deviations.

4. DISCUSSION

Values of both α_s and α_l of subjects B and G were greater than those of the other subjects and have almost the constant values, and these values of subjects D and

TABLE 5

Standard deviations of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, α_s *and* α_l *for each subject*

Subject	$\log([T_{sub}]_{p,m}/T_{sub}]_p)$	α_s	α_l
A	0·098	0·36	2·17
B	0·033	0·16	1·84
C	–	–	–
D	0·163	0·61	3·21
E	0·097	0·29	2·74
F	0·168	0·55	3·67
G	0·035	0·26	1·68
H	–	–	–

Note: Data for subjects C and H were not obtained.

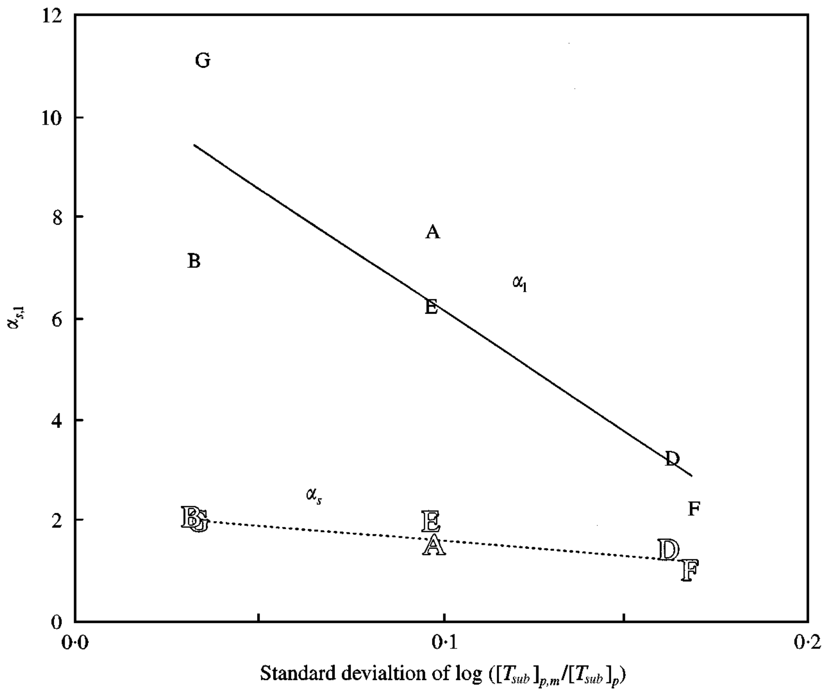

Figure 6 .Relationship between α_s and α_l, and standard deviation of preferred reverberation time on a logarithmic scale, $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, for each subject (except for subjects C and H). Solid line represents α_l (subjects A–H with $R^2 = 0{\cdot}76$) and dotted line represents α_s (subjects $\mathbb{A}$–$\mathbb{H}$ with $R^2 = 0{\cdot}70$).

F are significantly different in each set. The results of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, the values of α_s, and α_l in every four series for each subject are indicated in Figure 4. On both sides of the peaks, for subjects who have larger α, such as subjects B and G, the standard deviations of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ for each set are small. On the other hand, for subjects who have smaller α, such as subjects D and F, the preferable T_{sub} values are larger: 0·163 and 0·168 respectively.

Relationship between the standard deviations of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, α_s and α_l values for each subject (except subjects C and H) are plotted in Figure 6. Subjects with large α values, such as subject B or subject G, have smaller intra-individual changes, so that the standard deviations of preferable T_{sub} is small. On the other hand, subjects with small α values such as subjects D and F show minor preferences as T_{sub} changed. This result is similar to that of previous results for *SPL* [6].

The value of $[T_{sub}]_p$ calculated by using equation (1) with $(\tau_e)_{min}$ (= 23 ms) is 0·53 s. For the global subjects, the value of $[T_{sub}]_{p,m}$ obtained by the tests was 0·78 s, longer than the calculated value.

5. CONCLUSION

Subjects with large α values indicate smaller intra-individual changes, so the standard deviation of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ is small. On the other hand, subjects with small α values without sharp curves show minor preference as T_{sub} changed. The averaged value of preferred T_{sub} for vocal sources was 0·78 s, which is greater than the value (0·53 s) calculated by equation (1). Individual differences are observed in values of $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$ and α_s but not in value of α_l.

ACKNOWLEDGMENT

The authors wish to thank Mrs. Mikiyo Setoguchi as a soprano singer for her cooperation in recording source signals. This work is supported by the Ministry of Education, Grant-in-Aid for Scientific Research (C), 9838022, 1998.

REFERENCES

1. Y. Ando 1998 *Architectural Acoustics–Blending Sound Sources, Sound Fields, and Listeners* New York: Springer-Verlag, chapter 9.
2. Y. Ando and P. K. Singh 1997 *Music and Concert Hall Acoustics, Conference Proceedings of MCHA* 1995 (Y. Ando, D. Noson, editors). London: Academic Press, chapter 4. Global subjective evaluation for design of sound fields and individual subjective preference for seat selection.
3. M. Sakurai, Y. Korenaga and Y. Ando 1997 *Music and Concert Hall Acoustics, Conference Proceedings of MCHA* 1995 (Y. Ando, D. Noson, editors). London: Academic Press, chapter 6. A sound simulation system for seat selection.
4. Y. Ando, M. Okura and K. Yuasa 1982 *Acustica* **50**, 134–141. On the preferred reverberation time in auditoriums.
5. Y. Ando, K. Otera and Y. Hamana 1983 *The Journal of Acoustical Society of Japan* **39**, 89–95. Experiments on the universality of the most preferred reverberation time for sound fields in auditoriums (in Japanese with English abstract).
6. H. Sakai, P. K. Singh and Y. Ando 1997 *Music and Concert Hall Acoustics, Conference Proceedings of MCHA* 1995. (Y. Ando, D. Noson, editors). London: Academic Press, chapter 13. Inter-individual differences in subjective preference judgements of sound fields.
7. Y. Ando and P. K. Singh 1996 *Memoirs of the Graduate School of Science and Technology, Kobe University* **14**-A, 57–66. A simple method of calculating individual subjective responses by paired-comparison tests.

8. Y. Ando, T. Okano and Y. Takezoe 1989 *Journal of the Acoustical Society of America* **86**, 644–649. The running autocorrelation function of different music signals relating to preferred temporal parameters of sound fields.
9. K. Mouri, K. Akiyama and Y. Ando 1998 *Journal of Sound and Vibration* (Special Issue on Opera House Acoustics). Relationship between subjective preference the alpha-brain wave in relation to the initial time delay gap with vocal music.
10. P. Fraisse 1982 *The Physiology of Music* (D. Deutsch, editor). Orland, Fl: Academic Press, chapter 6, Rhythm and tempo.
11. Y. Ando 1985 *Concert Hall Acoustics*. New York: Springer-Verlag, chapters 3 and 4.
12. W. A. Glenn and H. A. David 1960 *Biometrics* **16**, 86–109. Ties in paired-comparison experiments using a modified Thurstone–Mosteller model.
13. L. L. Thurstone 1927 *Pschological Review* **34**, 273–286. A law of comparative judgment.
14. H. Sakai, H. Setoguchi and Y. Ando 1997 *Journal of the Acoustical Society of America* **102**, 3187. Subjective preference judgments of simulated sound field by listeners for sound source in opera performance.

APPENDIX A

For calculating the scale values of preference, a simple method [7] was used as an approximation for case V of Thurstone's law of comparative judgment [13]. It must be noted that the estimated scale value obtained by this method is smaller than the result estimated by the case V of Thurstone's law, though high correlation coefficient ($r = 0{\cdot}99$) was found between the scale values obtained from both methods. The results of two recent psychological tests [14], including this test with five sound fields show that the correlation ratio becomes about 1·26. This ratio may be mainly changed by the number of sound fields and individual differences.

APPENDIX B

In this article, the one-way analysis of variance (ANOVA) is adopted in order to evaluate individual differences in relation to the values of factors, $\log([T_{sub}]_{p,m}/[T_{sub}]_p)$, α_s and α_l as shown in Table 4. Its definitions and usage are briefly described here. By use of the ANOVA, significance tests of individual differences are conducted for the each factor which is categorized by each subject as levels.

At first, two hypotheses are set as follows. As the null hypothesis, each group, categorized by each subject, is considered to be sampled from one population. In this hypothesis, an individual difference is reserved. As the alternative hypothesis, each group is considered to be sampled from different populations. In this case, the null hypothesis is rejected and alternative hypothesis is adopted. Hence individual difference is accepted.

The values of F-ratio, F, are given as ratios of between-individuals variance and residual variance, calculated by the following equations:

$$F = s_A^2/s_E^2, \quad s_A^2 = S_A/df_A, \quad s_E^2 = S_E/df_E.$$

Here the values of S_A and S_E are given as a square-sum due to between-individuals variation and residual sum of squares respectively. The values of df_A and df_E are degrees of freedom of between-individuals variation and residual respectively. The F-ratio is a statistical value representing the difference among groups. If the null hypothesis is correct, the expected value of the F-ratio approaches unity, and the individual difference is reserved. If the F-ratio is greater than unity, it is considered that individual differences exists for the factor. Judgments of the tests are estimated by comparison between the F-ratio of samples and the F_p-ratio F_p. The value of F_p can be obtained from the well known F-distribution with df_A, df_E and a significant level as a probability, p. If the F-ratio is smaller than the F_p value, difference among subjects and judgement for significant difference are reserved. If the value of F is greater than that of F_p, difference among subjects can be obtained. In this case, the null hypothesis is rejected and the alternative hypothesis is adopted. The value of p that the F is greater than F_p, is obtained as an upper-sided probability of the F-distribution. Values of p smaller than 0·05 and 0·01 indicate significant differences of each factors among subjects with their probability of 5 and 1%, respectively.