Acoustical Psychology and Physiology in relation to Concert Hall Design
建築音響中的心理與生理

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Summary: Two factors have been composed of a standard of time are prevailing for designing a music hall; the initial time delay gap between the direct sound and the first reflection (t1) and the subsequence reverberation time (Tsub). In present study, a method for measuring human's responses on continuous brain waves (CBW) to change these two factors in music sound fields. It was applied here to analyze the autocorrelation function (ACF) of CBW in the -wave range and extend this relationship for a simply temporal sensation. First, the "effective duration" (e) was defined by the effective gap of the initial deduction (0.1 envelope) of ACF of CBW. Results show the analyses of e correlates well to the subjective preference of a music sound field (Motif B) by changing t1 and Tsub. The longer ($p < 0.01$) e were found as the SVs increased in the range of Tsub = 0.2 to 1.2 s. Finally, as the auditory tempo was varied, the differences of values of e shows a closer correlation ($r = 0.80$, $p < 0.01$) to the differences of SVs on the left hemisphere.

INTRODUCTION

The living environment is composed of elements involving spatial and temporal factors. The spatial standards are frequently employed to design as knowledge, but the temporal standard is not clear, and there is few theory formally adopted pertinently. Nevertheless, the temporal factors are obviously concerned with activities in the human's brain, in accordance with physical environment changes. For sound fields, four independent physical factors (Ando, Okano & Takezo, 1983; Chen, 1998) were prevailing for designing a sound field: (1) the initial time delay gap between the direct sound and the first reflection, t1; (2) the subsequence reverberation time, Tsub ; (3) the level of listening, LL; and (4) the magnitude of inter-aural cross-correlation (IACC). In particular, the first two factors have been composed of a standard of time. The subjective preference theory was effectively applied for the planning of a few music halls(Ando,1987; Ando, Sato, Nakajima & Sakurai, 1997; Toyama, Suzuki & Ando, 1995). As far as the temporal factors are concerned, the preference of sound fields can be calculated by autocorrelation function (ACF) of sound source signal together with such temporal factors. But it is weakness for subjective evaluation in general living environments entirely obtained by questionnaire using “language". Therefore, a method for measuring a human being's brain responses to external sound stimuli was arranged. The aim of present study is to identify the relationship between the subjective preference and the brain responses corresponding to the temporal variation in sound fields.

For the cerebral physiology corresponding to a sound environment, "auditory evoked potential (AEP)" has been used frequently. Electric potential is caused by the stimuli of voice, music, speech, tone pulse and so on. The potential of the auditory conduction path can be recorded by the summation method over a short time range (0 ~ 400 ms). Morrell and Salamy (1971) first recorded the slow vertex responses (SVR) with the AEP method on wide range scalp by 50 averaging. Ando (1992) has summarized all SVR data, and showed that the hemispheric dominances differed for different sound signals and acoustic factors of the sound field. And It also supports that the left hemisphere is mainly associated with speech and time sequential identifications and the right hemisphere is concerned with nonverbal and spatial identifications (Sperry, 1970).

However, these AEP researches could not be applied to a long physical quantitative variation above 400 ms. For example, the preferred reverberation time in an opera house is longer than 2 s. Therefore, it is necessary to observe continuous brain waves (CBW) which represent perception of the longer characteristics in a sound field. In CBW researches, there are plenty of problem relating to the psychological aspects of sensation, perception, attention, emotion, learning, intelligence, and personality. Lindsley (1952) concluded, with reliable psychological and neurophysiologic data, that the outstanding parameter of the data is time. This is especially true for frequency, the alpha rhythm's (-wave, 8 ~ 13 Hz) range varies during the range of behavioral states common to a normal adult. Ando (1985) applied the independent acoustic standards classified by the autocorrelation analysis and the inter-aural cross correlation of the sound signals to design a sound field. He also gives a model consisting of the autocorrelation mechanisms and inter-aural cross-correlation mechanisms of the two auditory pathways, and the specialization of human cerebral hemispheres for processing temporal and spatial factors of a sound field.

Therefore, the method applied here is to analyze the autocorrelation function of CBW in the a-wave range and extend this relationship for a simply temporal impression, tempo. In the standpoints of time consciousness, the time interval between two stimuli and the stimulus length (duration) are further examined. Fraisse (1982, 1984) summarized that the "preferred tempo" of human beings is detected at a similar rate to the naturally "voluntary tempo", which is in harmony with heart beat, walking rhythm, clapping hands, and so forth. Therefore, the subjective tempo is firstly identified the correlation between a reasonable evaluation for the simply temporal consciousness and the variation of the autocorrelation of CBW.

METHODOLOGY

(I) Subjective preference of the sound fields

According to the psychological present, the sound source was a 5 s peace of music, for 2 oboes, 2 horns, and strings from Arnold's Sinfornietta, Opus 48, from the beginning of the 3rd movement, which was recorded in an anechoic chamber at the BBC by Burd (1969). The most preferred delay time of the single reflection obtained in the paired-comparison tests is found centered on t1 = 35 ms, which corresponds to the minimum effective duration (e) of autocorrelation function (ACF) of the source signal, the echo disturbance effects are observed at t1 = 245 ms for 13 subject arranged by Ando (1977). Thus, these two physical standards were firstly selected for investigating the correlation between brain responses and them.

Secondly, to enhance the correlation, the preference scores of individual subject (a ~ j) were tested here. The reverberation time was changed at 7 levels from 0.2 to 3.2 s (listed in Table 1). The stimuli were each approximately 5.0 s duration as first step was used. The scale value (SV) of the subjective preference of each subject was calculated according to Case V of Thurstone's theory (1927). The results is shown in Figure 1, the most preferred Tsub was about 1.2 s averaged among 10 subjects. There is a certain degree of agreement for all subjects on the subjective judgment, especially, for scale values from 0.2 to 1.2 s. But, large individual differences for the differences of the scale values from 1.2 to 3.2 or 6.4 s are obvious.

Besides, depending on the purpose of preferred tempo, the white noise was provided for noise bursts in 10 ms as stimuli. All of them had every 3 ms arise interval and reduce decay with a 4 ms constant-amplitude (65 dB(A)) duration. The wideband noise was used since it is highly discriminable over a large range of duration detection (Hanna, 1984). Periods that begin on the onset to the next noise bursts were between 300 ms and 1,000 ms (300, 400, 550, 700, 850 and 1,000 ms). Sequential chains were all approximately 6.15 s, thus, the numbers of components in each sequence were 20, 14, 10, 8, 7 and 6. The scale value (SV) of the subjective judgments of each subject was calculated according to Case V of Thurston' s theory, and the model was reconfirmed by the goodness of fit (1951). As shown in Figure 1 and 2, the most preferred period was centered at 550 ms among 10 subjects. There is a certain degree of agreement among all subjects in the subjective judgments, more especially, the periods range from 300 to 550 ms. However, substantial individual differences for the scale values from 550 to 1,000 ms are obvious. Thus, the preferred model's suitability of the average preference scores was examined. The result of the goodness of fit indicated the model had a good match between fitted values and the observed values (2 = 12.9 < 2 10 (0.05) = 18.3).

Table 1 The setting of preference test for (a) initial delay gap of reflection, Δt_1 and (b) subsequence reverberation time, T_{sub}.

(a) Conditions of Δt_1 experiment

LL[dB]	Δt_1[ms]	IACC	A
75.0±0.2	35,245	≒1.0	1

(b) Conditions of T_{sub} experiment

LL[dB]	Δt_1[ms]	T_{sub}[s]	IACC	A
75.0±0.2	40	0.2,0.4,0.8,1.2,1.6,2.4,3.2	≒1.0	2

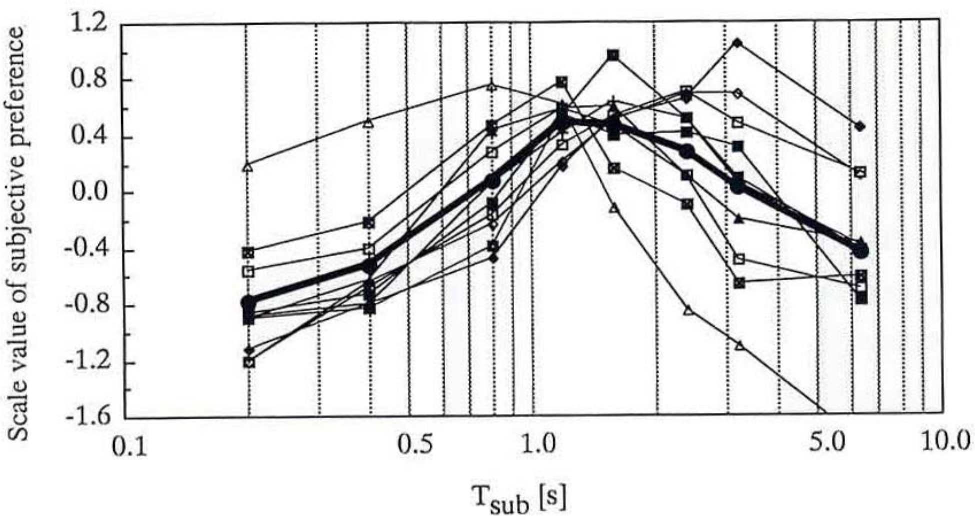

Fig 1 The scale vales of the subjective preference for reverberation time (Tsub) of 10 subjects different in respective experiment.

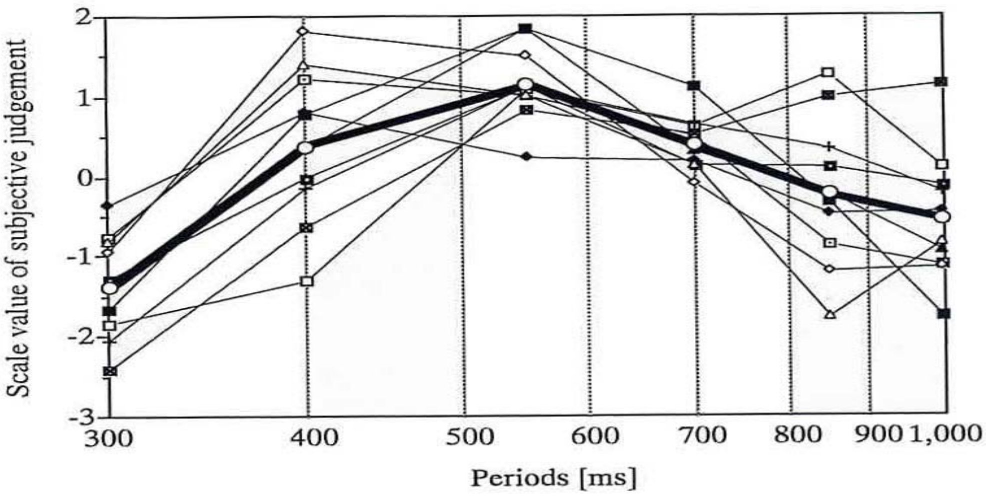

Fig 2 The scale vales of the subjective preference for preferred tempo of 10 subjects different in respective experiment.

(II) Recording and analyses of the CBW

The CBWs from the left and right cerebral scalps picked up by silver electrodes at T3 and T4 channels (The International 10 / 20 placement system (Jasper, 1958)) were amplified and recorded by a data recorder. The reference electrodes were positioned on both the left and right earlobes. The ground electrode was placed on the forehead. The CBW signals were analyzed after passing through a digital-band-pass filter with cut-off frequencies (140 dB/octave slops) of 8 ~ 13 Hz: -wave ranges. The sampling rate was 100 Hz for the ACF analyses. The leading edge of each stimulation trail was recorded simultaneously by a trigger signal.

To obtain a degree of similar repetitive features of the CBWs, the effective duration (e) of ACF of the -wave range in CBW was analyzed. Calculating e, only initial part of normalized ACF (approximately 0 to -5dB) showed the clearly decay for all data (Chen, 1996). Thus, the value of e defined at the ten-percentile delay (-10 dB) is obtained by fitting the straight-line regression for (Log(x( )) > - 5dB) or (< 500ms) of the ACF envelope for all; it involves a 2.5 s linear integral sum to correspond well to the stimulation by considering "psychological present". This procedure is similar to the manner of measuring the initial reverberation time in room acoustics.

According to paired-comparison method, the stimulus signals were presented by a running repetition of pairs. The same subjects as for the preference test participated. To find significant effects on CBW, we paired the most preferred stimuli and the worse (listed in Table 2). These kinds of pairs were presented successively every ten times in each series for simultaneous recordings of brain waves. The intervals between pairs were all set at 2 s. The subjects listened to three series (thirty pairs) with a 3-minutes interval between series as refreshment.

Table 2 The condition of EEG recordings on the T3 and T4 corresponding to changing Δt_1, T_{sub} and preferred tempo, all stimuli were about 5s.

Factors	Range of changed	Numbers of subjects
Initial delay time of single reflection (Δt_1)	35ms, 245ms	11
Subsequence reverberation time (T_{sub})	0.2s, 1.2s, 6.4s	10
Preferred tempo (Interval)	300, 550, 1000ms	10

Note: The values of above are all the setting condition

RESULTS

For the universality of the experimental identification, the values of e in the -waves range were examined by three-way analysis of variance (ANOVA) in a 10 x 2 x 2 level classification matrix for the factors of subjects, hemispheric difference (LR), and temporal factors. The results for each pair of stimuli are indicated in Table 3. It shows that significant differences between subjects and the effectively temporal variation for all, but none of significantly hemispheric difference. The reason is that there are interaction among LR and stimulus effects. To further discuss on interaction effects between LR and temporal factors, results of an one-way ANOVA on the accumulating values of e with respect to the left and right brain hemispheres for each pair of stimuli are analyzed. It is remarkable that effects of periods are only found in the left hemispheres.

Table 3 Results of the three-way ANOVA for the values of τ_e for the α-waves responding to the factors subjects, effects of T_{sub}, periods and hemispheric difference (LR, Left/Right) for pair of (a) T_{sub} and (b) periods (interval), respectively.

Source	Significant test	
	0.2 and 1.2s	1.2 and 6.4s
Subject	<0.001***	<0.001***
LR	0.149	0.159
Tsub	0.013**	0.894
Subject*LR	0.003***	0.032**
Subject*Tsub	0.271	0.004***
LR*Tsub	<0.001***	0.652

Source	Significant test	
	300 and 550ms	550 and 1000ms
Subject	<0.001***	<0.001***
LR	0.483	0.357
Tsub	<0.001***	<0.001***
Subject*LR	0.033**	<0.001***
Subject*Tsub	0.199	0.004***
LR*Tsub	0.328	0.344

Note: **p<0.05, ***p<0.01

DISCUSSION AND CONCLUSION

Depending on individual difference between subjects in preference tests and the results of the values of e in the -waves range mentioned above, the ratios of the e values of the -waves at (1.2 and 6.4 s) pair ([e (1.2 s) / e (6.4 s)]) correspond well to the differences in the scale values ([SV (1.2 s) - SV (6.4 s)]) for every individual as shown in Figure 3, where scale values for Tsub = 6.4 s are extrapolated using the behavior function proposed by Ando (1985). The similar results were also obtained from the ratios ([e (550 ms) / e (1,000 ms)]) of the averaged e values in the left hemispheres for each subject and the differences in scale values ([SV (550 ms) - SV (1,000 ms)]) of subjective preference. The correlation coefficient r = 0.80 (p < 0.01) in the left hemispheres, and r = - 0.12 in the right.

After all, the tendency at the preferred condition is consistent in studies in changing of the delay time of the single reflection (t1) and the subsequence reverberation time (Tsub) in a music sound field or at the preferred period of 550 ms. Regardless of physical parameters in the sound field, the left hemispheric dominance was based on the temporal point of view. Individual differences of subjective preference provide us the significant relationship to the ratios of the e values in -waves range obtained only in the left hemisphere. It is possible to outspread the time image of t1 and Tsub to the period by analyzing the e, ACF in the -wave range in relation to the subjective preference. The physiological method for environmental evaluation is further improved.

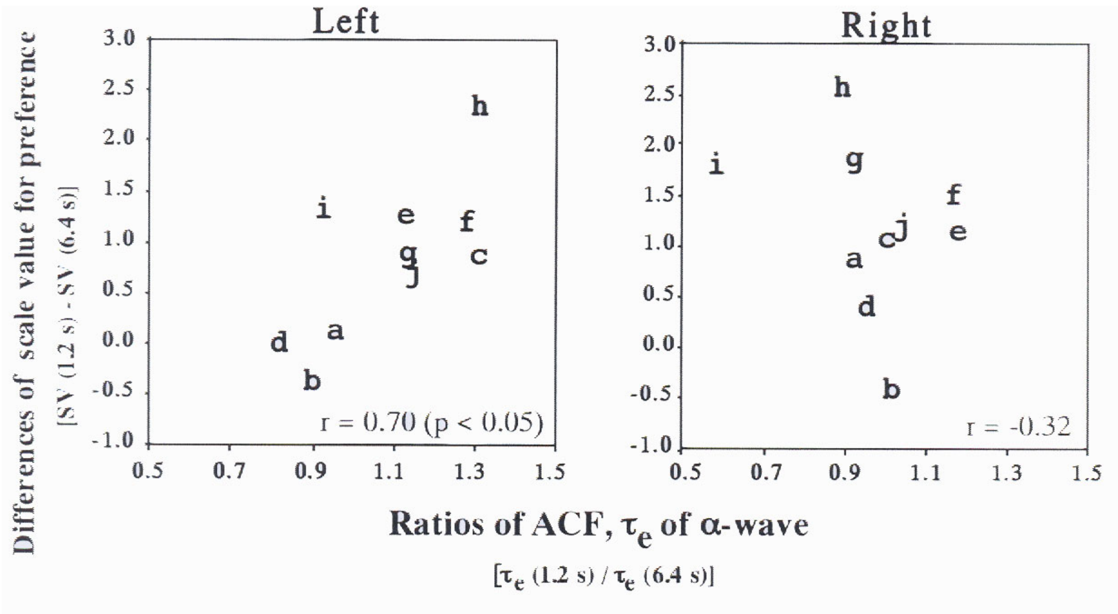

Fig 3 Relationship between differences of the scale values of preference [SV (1.2s) – SV(6.4s)] and radio of [τ_e (1.2s) / τ_e (6.4s)] of α-waves in left hemisphere for each subject.

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