Preferred Delay Time and Subjective Preference Judgment for Sound Field with Single Reflection

일차 반사음으로 구성된 음장에서의 최적지연시간과 주관 Preference의 판단

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ABSTRACT

In order to know the preferred delay time of single reflection in relation to the source signal, and to investigate whether or not there is any disparity in preference judgment of sound field between subjects of different nationalities, tests of subjective preference for musical sound fields with single reflection were performed. The result showed that the preferred delay times agreed with the effective duration of autocorrelation function of the source signals, when the amplitude of reflection relative to the direct sound is 0dB. No fundamental disparity in series of judgment of sound field was found even for different series of judgment with different music motifs. The result of preference test using different passages in single music showed that the fluctuation of the effective duration of autocorrelation function over all the passages of the music was small. Thus, the preferred delay time can be determined by the coherence of autocorrelation function of the source signals and the amplitude of reflection.

요 약

일차 반사음의 최적지연시간과 음장의 Preference 판단에 있어서 다른 민족간의 피험자 사이에 차이가 있는지를 알기 위해, 무향실에서 일차 측방반사음을 시뮬레이션하여 지연시간을 가변하면서 주관 Preference 실험을 하였다. 그 결과 일차 반사음의 최적지연시간은 반사음의 레벨이 직접음의 레벨과 같을때 음원의 자기상관함수(ACF)의 유효지속시간과 일치하며, 음악 모티프가 다르고, 판단 시리즈가 달라도 음장에 대한 Preference 판단에 기본적인 차이가 없는 것을 알았다. 또 하나의 음악 모티프에서 다른 2개의 패세지를 사용하여 Preference 실험한 결과, 음악 전체에 대한 ACF의 유효지속시간의 변동이 적음을 알았다. 따라서 일차반사음의 최적지연시간은 음원의 ACF와 반사음의 진폭으로 부터 예측할 수 있다.

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I. INTRODUCTION

Early reflection has the strongest level and is an important factor in the acoustic evaluation of a room. The initial delay time is defined as the difference in the time of arrival at a listener's position between the direct sound and the first-reflection sound. It is obtained by $\Delta t_1=(d_1-d_0)/c$, where d_1 is the path length of the first-reflection, d_0 is the distance between the source and the position of the listener, and c is the sound velocity. The importance of early lateral reflections in concert halls has been demonstrated by several investigators. Beranek[1] initially suggested that the initial delay time as a measure of intimacy was the most significant factor of a concert hall (more significant than reverberation time). For optimum delay, he claimed that the initial delay time gap must be less than 20 ms. The importance of early lateral reflections was further investigated by Barron [2]. He has reported that the early reflections arriving between 10 and 80 ms contribute to the enhancement of direct sound and the subjective diffuseness.

Gottlob[3] has carried out a subjective evaluation between concert halls in an attempt to correlate the subjective data with the objective parameters of the halls. However, in his result, initial delay time did not appear as a significant factor because recording positions were selected only around the centers of the halls (i.e., initial delay times were limited in a certain range). None of the studies so far mentioned examined the optimal delay time in relation to the source programs. In a more recent study, Ando[4-9] has shown that the preferred initial delay time in a concert hall varies according to the type of source programs and depends on the autocorrelation function of the source signals.

In this paper, in order to know the preferred delay time of the single reflection in relation to the autocorrelation function (ACF) of source signal and to investigate whether or not there is any subjective preference disparity for the sound field between subjects of different nationalities, tests of subjective preference for musical sound field with single reflection were performed with Korean and German subjects. The results of preference judgments for the subjects from both nations including the data of Japanese subjects[9] are compared.

II. PROCEDURE

A. Music Motif

Suppose that a single sound source is located in front of a listener in a room. Let $w_n(t)$ be impluse responses describing the reflection property of boundaries. Let $h_{nL}(t)$ and $h_{nR}(t)$ be the impulse responses from a free field to the left and right ear-canal entrances respectively, n denoting a single sound reflection with a horizontal angle ξ and an elevation angle η with respect to the listener, and n=0 referring to the direct sound with $\xi=0^\circ$ and $\eta=0^\circ$. Then, the sound pressure at left(L) and right(R) ears, $f_{L,R}(t)$, is expressed by the following equation [4]

$$f_{L,R}(t)=\sum_{n=0}^{N} p(t)*A_n w_n(t-\Delta t_n)*h_{nL,R}(t) \qquad (1)$$

where p(t) is a source signal and the asterisk denotes convolution. A_n and Δt_n are the pressure amplitude and the delay time of the reflections relative to the direct sound, respectively.

Source signal p(t) can be represented by its long-time autocorrelation function:

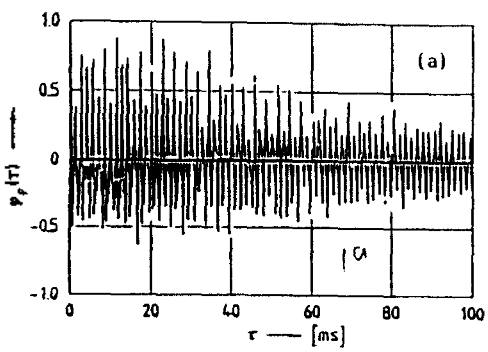
$$\Phi_p(\tau)=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T} p'(t)p'(t+\tau)dt \qquad (2)$$

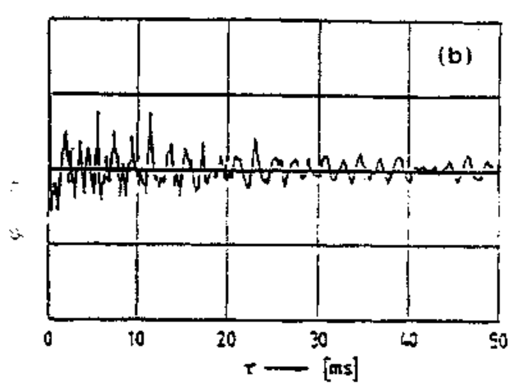
where $p'(t)=p(t)*a(t)$ and a(t) corresponds to the ear sensitivity, which might be characterized by the external ear and the middle ear. For practical convenience, a(t) is chosen as the impulse response of an A-weighting filter. The object of the autocorrelation function is to evidence whether repeatability exists in the signal under examination, that is, the ACF is regarded as a kind of reverberation contained within the source. The ACF depends on the music style, tempo, rhythm and other characteristics of the signal.

The above equation may be divided into the intensity of the source signal $\Phi_p(0)$, and the normalized autocorrelation function is defined by

$$\phi_P(\tau) = \Phi_P(\tau)/\Phi_P(0) \quad (3)$$

The denominator term acts to normalized function, thereby bounding it between one (at τ=0) and zero. The effective duration of the ACF is defined by the delay τ_e at which the envelope of the normalized ACF $\phi_p(\tau)$ becomes 0.1[5]. In this experiment, three music motifs were used, as listed in Table 1, which are well-known BBC anechoic chamber recordings and have different ACFs. The long-time ACF of 35-second duration (2T=35 s) was measured with an A-weighting filter. Measured long-time ACFs are shown in Fig. 1 for each music motif listed in Table 1. The values for the motifs are also listed in Table 1.





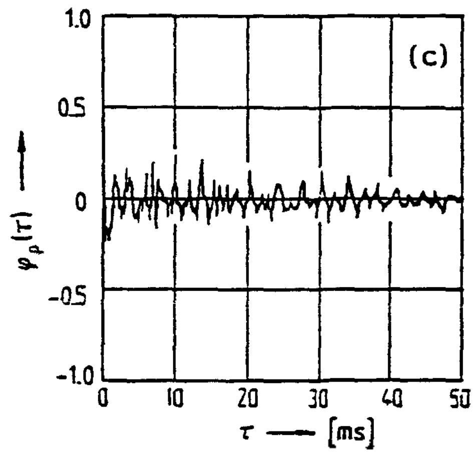


Fig. 1. Measured autocorrelation functions of music motifs. (a) Music motif A. Royal Pavane by Gibbons, τ_e=127 ms; (b) music motif B, Sinfonietta. Op. 48, by M. Arnold, τ_e=35 ms, (c) music motif C. Symphony No. 40 in C major by W.A. Mozart, τ_e=38 ms.

Table 1. Music motifs used and the effective duration of ACF

Motif	Composer	Title	τ_e (ms)
A	Gibbons	Royal Pavane	127
B	Arnold	Sinfonietta	35
C	Mozart	Symphony in C Major "Jupiter"	38

B. Test of Subjective Preference

Two loudspeakers, which produce direct frontal sound (azimuth angle ξ=0°, vertical angle η=0°) and single reflection (ξ=36°, η=0°), were arranged in an anechoic chamber. The amplitude of the reflection (A_1) was adjusted to be the same as that of direct sound, i.e., A_1=1.0. The delay time of single reflection was adjusted in the range of 0 to 250 ms (10 different delays) in the case of Korean subejects, and 0 to 256 ms (6 different delays) in the case of German subjects. As the number of pairs is n(n-1)/2 for complete comparison, we have forty-five pairs for Korean subjects and fifteen pairs for German subjects. The sound field pairs were presented to the listeners in random order in the anechoic chamber. When listening to the music, the subjects were required to judge which of the two sound fields they preferred. The score for a preferred sound field is +1 and -1 for the other. The paired comparison tests were performed with 7 Korean subjects and 13 German subjects. The first 12 seconds of motifs were chosen as source signals. The sound pressure level presented to the subject was adjusted to a peak value of 80 dB(A).

III. RESULTS AND DISCUSSION

A. Consistency and Agreement of Preference Data

First of all, in order to achieve the consistency of judgment in a set of comparative judgments for each subject, the significant test for the consistency was applied[10]. As the results of the test, the scale value could be figured out with 5 subjects for Motif A and 6 subjects for Motif B among the German subjects, in which a certain degree of consistency in each subject was observed (5% significance level). On the other hand, the consistency of judgments among all the Korean subjects was satisfactory. Also, in order to know the extent of agreement among the subjects with respect to their comparative judgment of different sound fields, the significant test for agreement was applied[10]. The result revealed that the subjects of both nationalities showed significant agreement (5% significance level).

Then, with the probabilities obtained by the paired comparison tests, the scale values of preference were obtained using Thurstone's Case V[11]. The test of goodness of fit for the data obtained by the Case V model showed that our observed data were satisfactory (5% significance level)[12].

B. Agreement of Preference between Different Subjects

In order to compare the most preferred delay time of a single reflection with Korean and German subjects, the same passage of music motif A was used. The resulting scale values of preference are shown in Fig. 2. The most preferred delay times found are about 120 ms and about 128 ms for Korean subjects and German subjects, respectively. These preferred delay times agree fairly well with both groups of subjects. The preferred delay times nearly correspond to the effective duration (τ_e=127 ms) of ACF for Motif A.

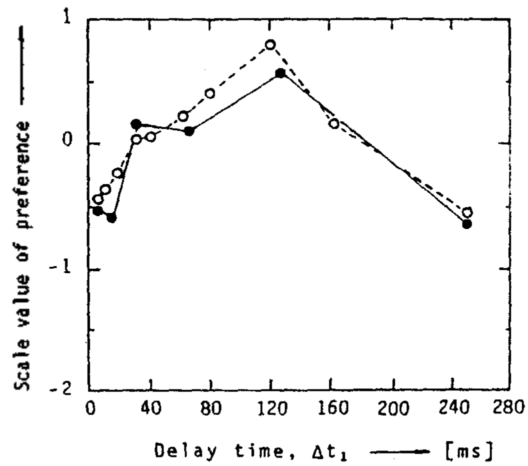


Fig. 2. Scale values of preference obtained by different subjects as a function of delay time. ○: Korean subjects, ●: German subjects.

In spite of the different nationalities of the subjects, these most preferred delay times coincide well the effective duration of ACF, so that the preferred delay time for any group can be given by the same formula, i.e., in general, the most preferred delay time $[\Delta t_1]_p$ is

$$[\Delta t_1]_p = \tau_p \qquad 1$$

such that

$$|\phi_p(\tau)|_{envelope} = 0.1A, \quad \text{when } \tau = \tau_p$$

where $\phi_p(\tau)$ is the normalized ACF of source signals. Its amplitude may be chosen by

$$A = [\sum_{n=1}^{\infty} A_n^2]^{1/2} \quad (5)$$

As similar manner to Eq.(4), the most preferred delay time of the first reflection for alto-recorder solists is tentatively given by[13],

$$|\phi_p(\tau)|_{envelope} = 0.3A_1, \text{ at } \tau = \tau_p \quad (6)$$

Thus, shorter delay time is preferred for performers than for listeners. It is considered that the performers are more sensitive to the reflection than the listeners.

The various subjective effects associated with the monaural interaction of a sound with its repetition after a certain delay Δt have been discussed in earlier studies[5][14][15]. The effects of a delay sound which give a negative contribution to the sound quality were reported as follows: for $0<\Delta t_1<\tau_p$, a coloration (i.e., a characteristic change of the signal spectrum) or image shift (i.e., source moved from the direct sound towards the reflection sound) occurs since the direct sound is followed by a strong isolated reflection. The perception of coloration has been shown by Atal et al.[14], who reported that the perceived coloration caused by a reflection depends not only on the time delay but also on the reflection amplitude. Recently, Kates[15] has introduced a model of auditory system to predict the perception of coloration. His model called the central spectrum model is based on auditory signal processing and incorperates a critical-band filter-bank, synchronized firing rates, and temporal integration, which has accurately predicted the perception of coloration in Gaussian noise. For $\Delta t_1 \rightarrow 0$ ms, the preference becomes lower since interaural crosscorrelation (IACC) increases, as shown in Fig. 3. An echo disturbance effect is observed if Δt_1 exceeds τ_p.

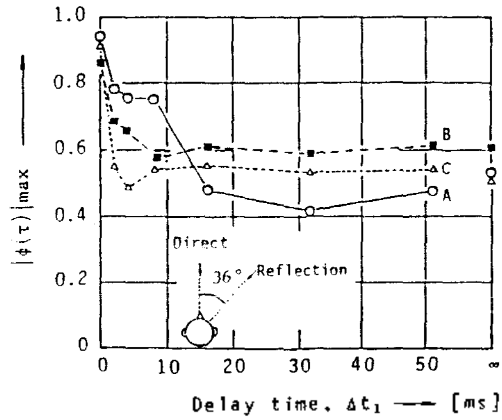


Fig. 3. Measured values of the IACC of the music sound field as a function of the delay of single reflection (ξ=36°). Values at $\Delta t_1 \rightarrow \infty$ are calculated values (see Reference [4]). A to C are different music motifs. Note that as the delay time approaches zero, the values of IACC rapidly increase. From Ando[5].

C. Agreement of Preference between Different Passages of Single Music

For the purpose of reconfirming the validity of the above formula (Eq.4), further preference tests using two different passages of music motif C were performed with only the Korean subjects. The first passage, from 0 to 10 seconds, and a later passage, from 40 to 50 seconds, of the music were chosen as source signals. The resulting scale values of preference are shown in Fig. 4. The most preferred delays obtained were about 30 ms and 40 ms in the first 10 seconds and the later 10 seconds of music. These results may be due to the fluctuation of effective duration of the running autocorrelation function in each passage. However, it is considered that such fluctuation of effective duration which could be related the musical score may be limited within a certain range in the whole passage of music or the kind of source signals. Therefore, the most preferred delays can be approximately found by Eq.(4) with the value of τ_e (38 ms) which is representative for the first 35 seconds of music(see Table 1).

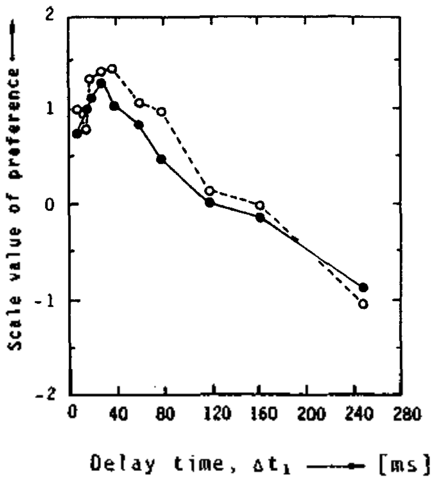


Fig. 4. Scale values of preference obtained with different passages of the music. (7 Korean subjects). Part 1 (○): the first passage (0 to 10 seconds). Part 2 (●): the second passage (40 to 50 seconds).

D. Consistency of Scale Value of Preference

In order to examine the resemblance of scale values obtained here, even not at the most preferred delay, the delay time was normalized by the most preferred delay time and the scale values at the most preferred delay time were adjusted to zero. The result is plotted in Fig. 5. Reasonable agreement between the scale values for Korean, German and also Japanese subjects is found. The data for Japanese subjects (eight subjects) in the figure were rearranged from Reference [9] The data with a continuous speech signal were also plotted in the figure (symbol +), which are the result of preference test for Japanese subjects (eight subjects) with speech signal (see Fig. 3.3 of Reference [16]. Thus, it may be said that there is no fundamental disparity in subjective preference judgments. This result, in turn, reveals the unit of scale values is nearly constant even for different series of judgments with different music motifs.

Accordingly, a common formula may be found by the average values (solid curve in Fig. 5) as in the following approximation:

$$S_1 \simeq -\gamma |X|^{3/2} \qquad (7)$$

where

$$X = \log(\Delta t_1 / [\Delta t_1]_p)$$

and

$$\gamma \simeq 1.5, \text{ for } X \leqq 0;$$
$$\gamma \simeq 2.2, \text{ for } X > 0.$$

Note that the coefficient γ indicated above may be adapted for the sound field with single reflection.

As expressed in Eq. (7), the scale value of preference is proportional to the 3/2 power of the normalized objective parameter, which is expressed as a logarithmic function of the initial delay time.

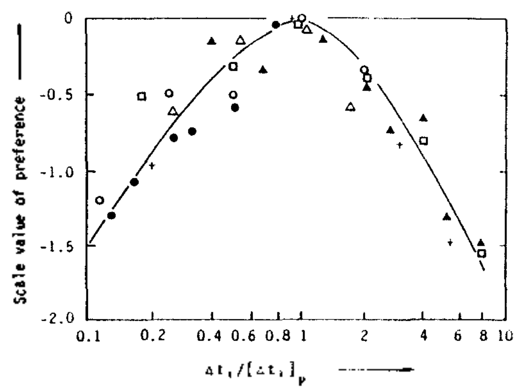


Fig. 5. Scale values of preference as a function of the delay time normalized by its most preferred delay. Different symbols indicate the scale values obtained by different test series with different music motifs. The data for a speech signal are also plotted in the figure.
○,●: Music A; △,□: Music B; ▲: Music C; +: Speech. ●,▲: Korean subjects; ○,□: German subjects; △,+: Japanese subjects.

IV. CONCLUSION

The most preferred delays of single reflection agreed well with different subjects and coincided with the effective duration of autocorrelation function (ACF) of sources, when the amplitude of reflection $A_1=1$. The preferred time delay could be predicted by a single formula regardless of the nationalities of the subjects. It should be noted the number of reflections in real halls is infinite and that the first strong reflection does not always occur. When the first reflection is not the strongest one, the initial delay time does not have significance. Gottlob adopted the reflection that is not more than 10dB below the direct sound as the initial reflection[3].

The preferred delay times of the first reflection were reasonably consistent with the effective duration of ACF of sources irrespective of incident angles because of monaural criterion [16]. However, as far as the binaural criterion (Interaural Crosscorrelation) is considered, it may preferably be a lateral than nonlateral reflection.

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