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SUBJECTIVE PREFERENCE OF CELLISTS FOR THE DELAY TIME OF A SINGLE REFLECTION IN A PERFORMANCE

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To provide knowledge useful in designing the stage enclosure in a concert hall, Nakayama reported the subjective preference of alto-recorder players for sound fields with a single reflection [*Acustica* **54**, 217–221 (1984)]. The present study evaluates the subjective preferences, with regard to ease of performance, of five cello soloists for the delay time of a single reflection. The scale values of preference for the delay time of a single reflection were obtained using a paired comparison method, and the results were compared with those for the alto-recorder players and listeners. The scale values of preference for both individuals and for global cellists with regard to the delay time of reflection can be expressed by a single approximate formula, normalizing the delay time by the most-preferred delay time observed for different music motifs. A notable finding is that the most-preferred delay time of a single reflection for each cellist can be calculated from the amplitude of the reflection and the minimum value of the effective duration $(\tau_e)_{min}$ of the running autocorrelation function of the music motifs played by each cellist.

1. INTRODUCTION

In order to make an excellent concert hall, we need to design the sound fields not only in the audience area but also in the stage area for performers. The primary issue is that the stage enclosure should be designed to provide a sound field in which performers can play easily.

Marshall *et al.* [1] investigated the effects of stage size on the playing of an ensemble. The parameters related to stage size in their study were the delay time and the amplitude of reflections. Gade [2] used a laboratory experiment to investigate the preference of performers for the total amplitude of the reflections. On the other hand, the preferred delay time of a single reflection for listeners can be calculated from the effective duration of the long-time autocorrelation function (ACF) of the source signal and the amplitude of reflections [3–5]. When music signals contain a large fluctuation in tempo, it is more accurately expressed by the

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minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of source signal [6]. Nakayama [7] showed that the preferred delay time of a single reflection for alto-recorder soloists can be determined from the amplitude of the reflection and the duration of the long-time ACF of the source signal.

The present study examines whether or not the preferred delay time of a single reflection for each cello soloist can be calculated from the amplitude of the reflection and the minimum value of the effective duration of the running ACF of the music motifs played by the cellist.

2. EXPERIMENT

2.1. MUSIC MOTIFS

Music motifs were characterized in terms of the running ACF of the source signal played. The same music motifs (motifs I and II) used in the experiments conducted by Nakayama [7] were used here also. The tempo of motif I was faster than that of motif II as shown in Figure 1. The two music motifs played by each of five cellists were picked up by a microphone in front of the cellist. The distance between the microphone and the center of the cello body was 0·50 ± 0·01 m. The music tempo

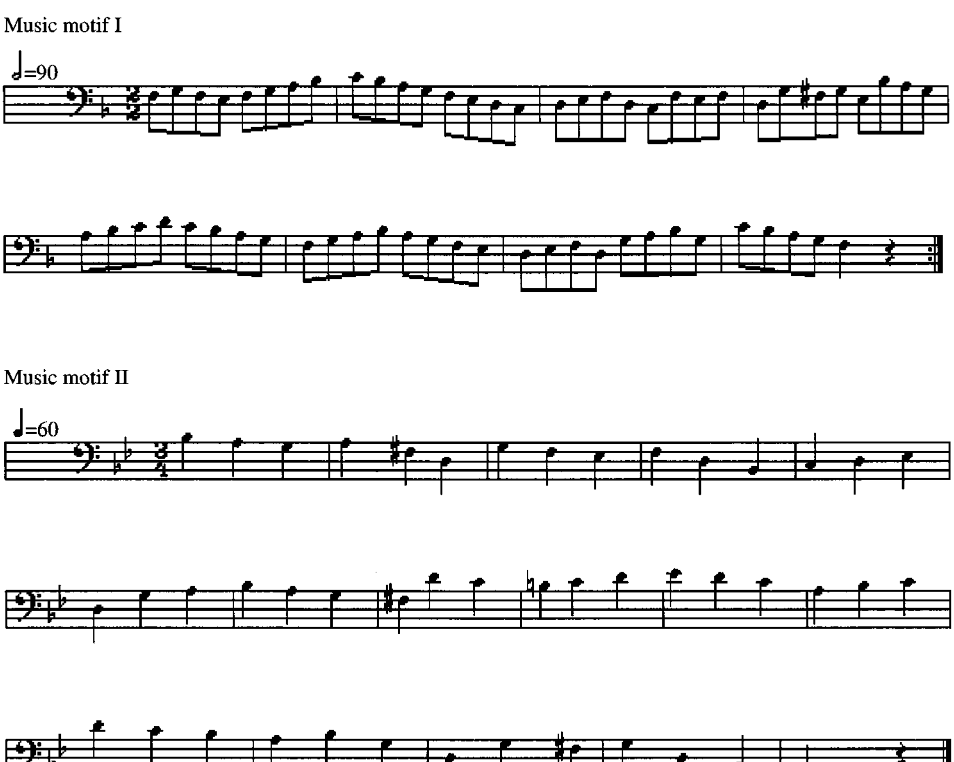

Figure 1. Music scores of motifs I and II composed by Tsuneko Okamoto [7].

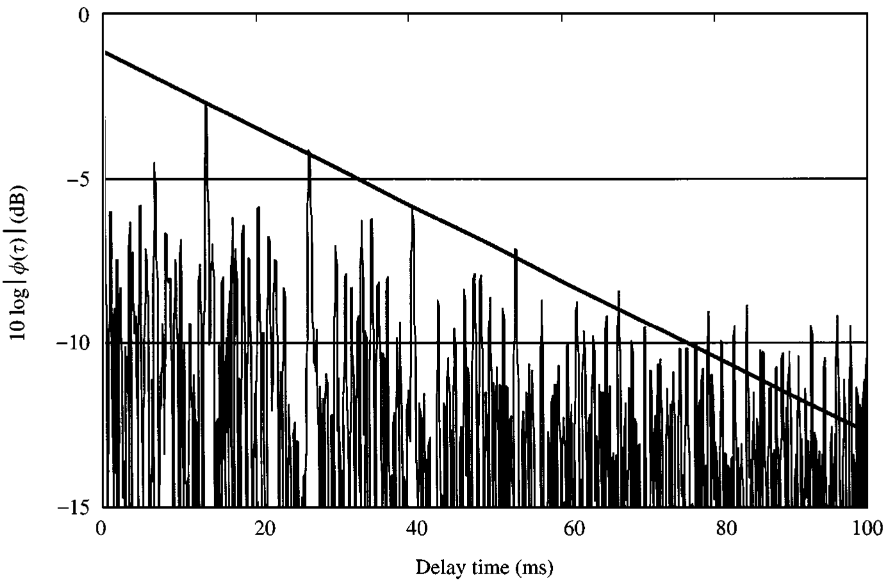

Figure 2. Example of determining the effective duration of the running ACF.

was maintained with the help of a visual (silent) metronome. Each music motif was played three times by each cellist. The minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of a music signal is the most active part of the music signal, containing important information and influencing the subjective attributes related to the temporal factors [6]. The effective durations of the running ACFs of the music signals, after passing through an A-weighted network, were calculated. The running integration interval of ACF 2T was 2·0 s. This interval was chosen according to the results of several previous investigations [6, 8]. Figure 2 demonstrates an example of the logarithm of the absolute value of the ACF plotted as a function of the delay time. The envelope decay of the initial part of the ACF can be fitted by a straight line in the range from 0 to $-$ 5 dB, and the effective duration τ_e of the ACF can be easily obtained from the decay rate extrapolated at $-$ 10 dB [9]. Examples of effective durations of the running ACF for music motif I played by subjects B and E are shown in Figure 3. The minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF for each cellist and each session are listed in Table 1. For all cellists, the effective durations $(\tau_e)_{min}$ for music motif I were shorter than those for music motif II. Mean values of $(\tau_e)_{min}$ were 46 ms for music motif I and 84 ms for music motif II, and for both motifs the ranges of $(\tau_e)_{min}$ are within $\pm$ 5 ms. Individual differences in the effective durations of the running ACF may depend on the performer's style.

2.2. PROCEDURE

The single reflection from the back wall in the stage enclosure was simulated in an anechoic chamber by a loudspeaker 0·80 $\pm$ 0·01 m from the head of the cellist.

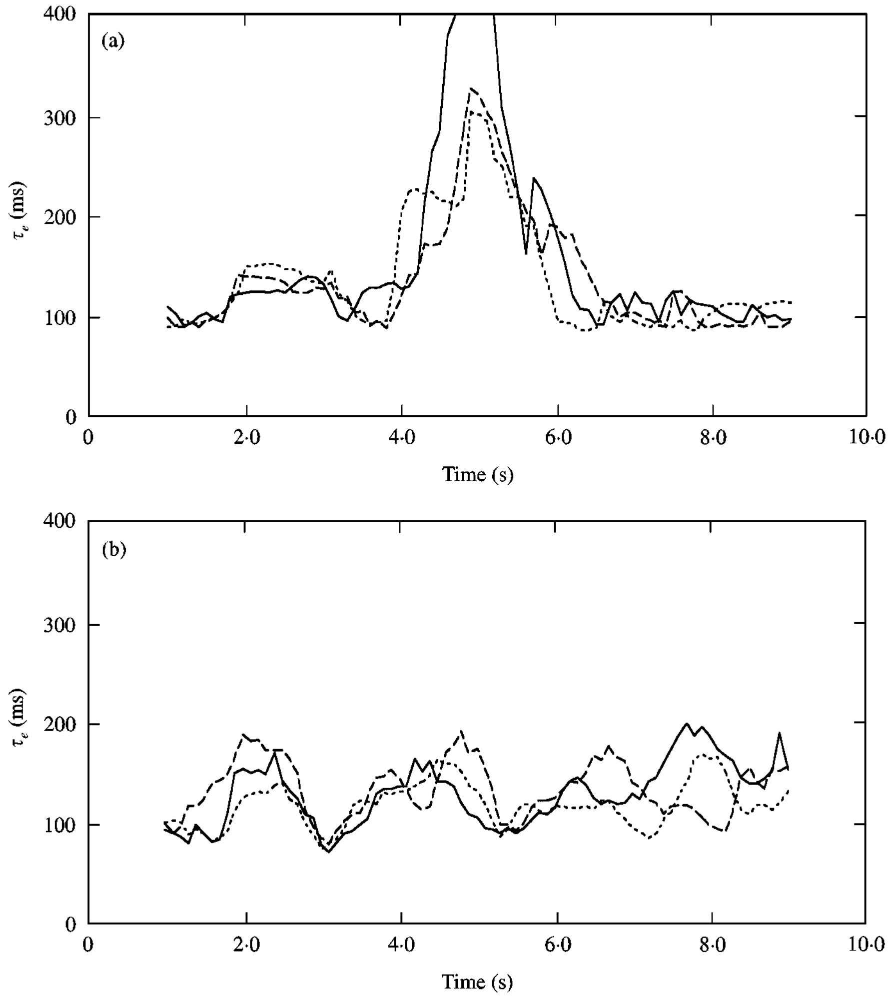

Figure 3. Examples of the measured effective duration of the running ACF with a 100 ms interval as a function of the time. Each music motif was played three times by each cellist. (——): first session; (- - - - -): second session; (······): third session. (a) Music motif I for subject B, $(\tau_e)_{min} = 50 \pm 2$ ms; and (b) music motif I for subject E, $(\tau_e)_{min} = 37 \pm 1$ ms.

The sound signal was picked up by a 1/2-in condenser-type microphone at the entrance of the performer's left ear and was reproduced by the loudspeaker after passing through a digital delay device. The amplitudes of reflection A_1, relative to that of the direct sound measured at the entrance of the performer's left ear, was kept constants at -15 and -21 dB when the cellist played a musical note "a" (442 Hz).

2.3. PAIRED COMPARISON TESTS

Paired comparison tests were conducted for the five sound fields listed in Table 2. The delay times of the reflection differed between cellists according to the $(\tau_e)_{min}$ of

TABLE 1

Minimum values of running τ_e of ACF for music motif played by each cellist

Cellist	Session	Music motif I (ms)	Music motif II (ms)
A	1st	35	90
	2nd	41	96
	3rd	41	89
B	1st	52	92
	2nd	49	87
	3rd	49	89
C	1st	37	89
	2nd	38	86
	3rd	36	93
D	1st	57	87
	2nd	56	85
	3rd	54	86
E	1st	37	71
	2nd	38	74
	3rd	36	79
Averaged		46	84

TABLE 2

Range of delay times of reflection variation due to the $(\tau_e)_{min}$ of each cellist in subjective preference judgments

Music	A_1 (dB)	Values of delay times of reflection (ms)				
Motif I	– 15	11·8 ± 0·8	24·0 ± 2·0	48·0 ± 4·0	72·0 ± 6·0	96·0 ± 8·0
	– 21	15·6 ± 4·4	33·6 ± 7·4	67·2 ± 6·0	100·8 ± 22·2	134·4 ± 29·6
Motif II	– 15	19·4 ± 2·6	39·4 ± 5·6	78·8 ± 11·2	118·2 ± 16·8	157·6 ± 22·4
	– 21	23·6 ± 3·4	47·8 ± 7·2	95·6 ± 14·4	143·4 ± 21·6	191·2 ± 28·8

the running ACF obtained in advance since the preferred delay time of a single reflection is determined from the $(\tau_e)_{min}$ of the running ACF of source signal. The five subjects were asked to decide which of two sound fields would be easier for them to perform in. The test consisted of 10 pairs ($N(N-1)/2$, $N = 5$) of stimuli in total, and for all subjects the test was repeated three times interchanging the order of the pairs. It took about 20 min for each cellist and for each music motif.

3. RESULTS AND DISCUSSION

Fifteen responses (5 subjects × 3 repeats) to each sound field were obtained and were confirmed by consistency tests. The scale values of preference for each cellist

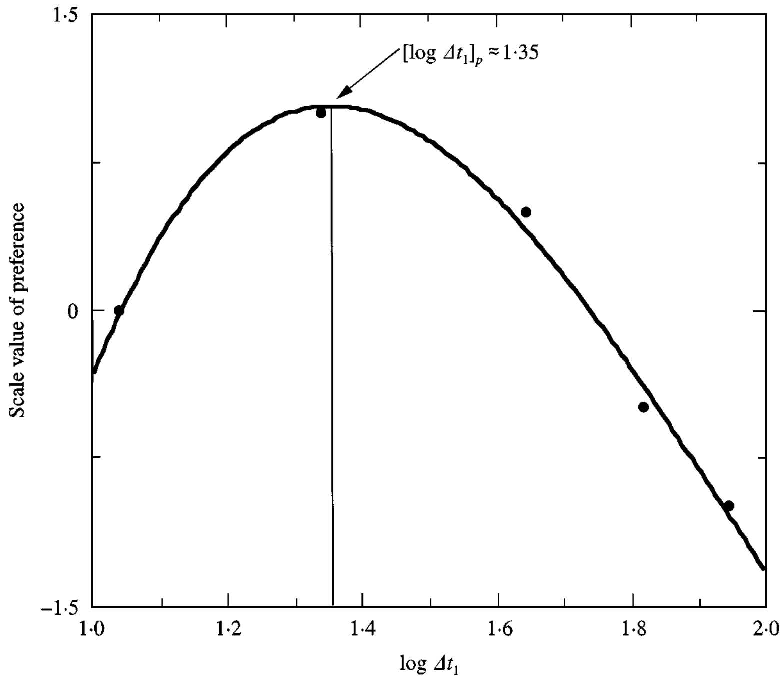

Figure 4. Example of the regression curve for the preferred delay time (subject D, music motif I, − 15 dB). $[\log \Delta t_1]_p \approx 1{\cdot}35$, thus $[\Delta t_1]_p \approx 22{\cdot}6$ (ms).

were obtained by applying the method that Ando and Singh proposed for modifying the Thurstone method. It is expressed by [10]

$$S_i = \sqrt{2\pi}(2T_i - N)/2N, \tag{1}$$

where T_i denotes the total score for sound field *i*, with wins counting 1, draws (comparisons of the same sound fields) 0·5, and losses 0, and where *N* is the number of sound fields.

Figure 4 shows an example of the regression curve for the scale value of preference and the method of estimating the most preferred delay time $[\Delta t_1]_p$. The peak of this curve denotes the most-preferred delay time. The most-preferred delay times for individual cellists and the global preference results are listed in Table 3. Global and individual results (except for that of subject E) for music motif II were longer than those for music motif I.

The most-preferred delay time of a single reflection is described by the duration τ'_p of the ACF, which is expressed by

$$[\Delta t_1]_p = \tau'_p \tag{2}$$

such that

$$|\phi_p(\tau)|_{envelope} \approx kA'^c \quad \text{at} \quad \tau = \tau'_p. \tag{3}$$

TABLE 3

Judged and calculated preferred delay times of a single reflection for cello soloists. Calculated values of $[\Delta t_1]_p$ are obtained by equation (4) using the amplitude of the reflection A_1, and $(\tau_e)_{min}$ for music signal performed by each cellist

				Judged $[\Delta t_1]_p$ (ms)		Calculated $[\Delta t_1]_p$ (ms)	
A (dB)	A' (dB) ($=A+10$)	A'	Cellist	Motif I	Motif II	Motif I	Motif II
			A	16·2	47·9	16·3	38·5
			B	< 12·0	73·8	35·2	62·7
− 15	− 5	0·56	C	< 12·0	60·8	21·3	51·3
			D	22·6	38·2	35·1	53·9
			E	17·6	63·6	17·3	35·2
			Global	18·0	48·3	24·3	47·5
			A	18·1	48·4	21·8	51·5
			B	61·2	105·0	59·3	105·6
− 21	− 11	0·28	C	—	77·9	—	80·6
			D	74·6	86·8	56·9	87·4
			E	< 14·0	42·2	24·8	50·2
			Global	30·4	71·8	37·6	73·4

The values k and c are constants that depend on the subjective attributes [5]. The value of A' is the amplitude of the reflection being defined by $A' = 1$ relative to − 10 dB of the direct sound as measured at the ear's entrance. This is due to the over-estimation of the reflection by the performer [7]. If the envelope of the ACF is exponential, equation (3) simply yields

$$\tau'_p = \left(\log_{10}\frac{1}{k} - c\log_{10}A\right)\tau_e. \tag{4}$$

According to a previous study [6], the effective duration τ_e of the long-time ACF in equation (4) is replaced by the minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of music used for judgments. Upon using the quasi-Newton method, the values $k \approx 1/2$ and $c \approx 1$ are obtained. It is worth noting that the coefficients k and c for alto-recorder soloists were respectively 2/3 and 1/4 and for listeners were respectively 0·1 and 1. After setting $k = 1/2$, we obtained the coefficient c for each individual as listed in Table 4. The average value for the five cellists was 1·06. This value corresponds to the global results. The relation between the most-preferred delay time $[\Delta t_1]_p$ obtained by preference judgment and the duration τ'_p of the ACF calculated by equation (4) using $(\tau_e)_{min}$ is shown in Figure 5. Different symbols indicate the values obtained in different test series. The correlation coefficient is 0·91 ($p < 0{\cdot}01$). The scale values of preference for each of the five cellists as a function of the delay time of a single reflection normalized by the calculated $[\Delta t_1]_p$ are shown in Figure 6. Different symbols indicate the scale values obtained

Table 4

Coefficients c for individual and global results, when $k = \frac{1}{2}$

	Cellist					Averaged (global)
	A	B	C	D	E	
c	0·47	1·61	1·10	1·30	0·67	≈ 1

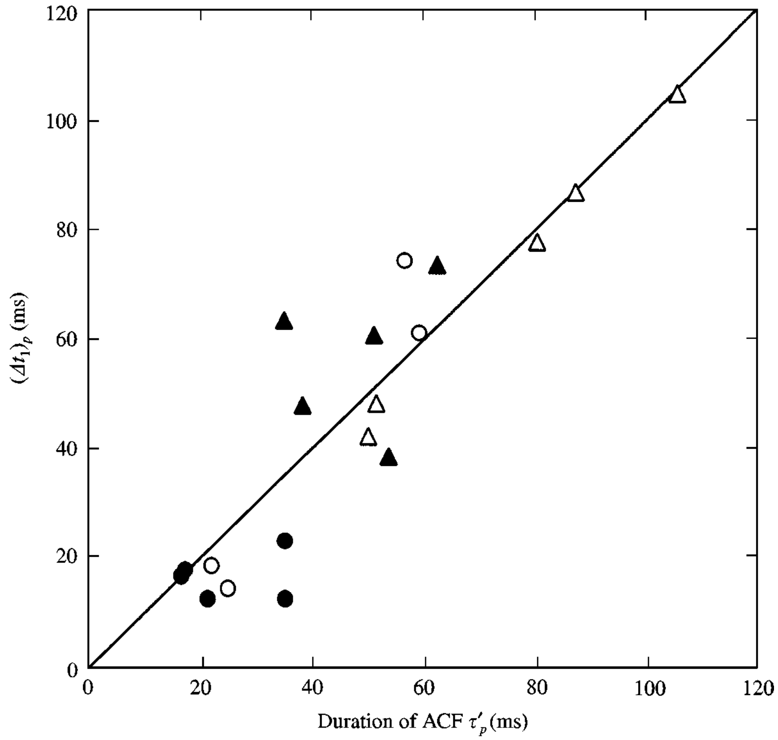

Figure 5. Relationship between the most preferred delay time $[\Delta t_1]_p$ and the duration τ'_p of the ACF calculated by equation (4). Correlation coefficient, $r = 0{\cdot}91$ ($p < 0{\cdot}01$). ●, Music motif I, -15 dB; ○, music motif I, -21 dB; ▲, music motif II, -15 dB; △, music motif II, -21 dB.

in different test series. Each symbol has 25 data (5 subjects × 5 sound fields) except for the amplitude of -15 dB for music motif I (for which there were 20 data because consistency tests did not indicate a significant ability to discriminate preference in the results of subject C). The scale values obtained in different test series are consistent with each other. The regression curve is expressed by [5]

$$S \approx -\alpha |x|^{3/2}, \tag{5}$$

where $x = \log \Delta t_1 / [\Delta t_1]_p$ and the weighting coefficient α is 2·3 for $x \geqslant 0$ and 1·0 for $x < 0$.

Figure 7 shows the relative amplitude of a single reflection for the preference of cello-soloists as a function of the delay time of a single reflection normalized by the

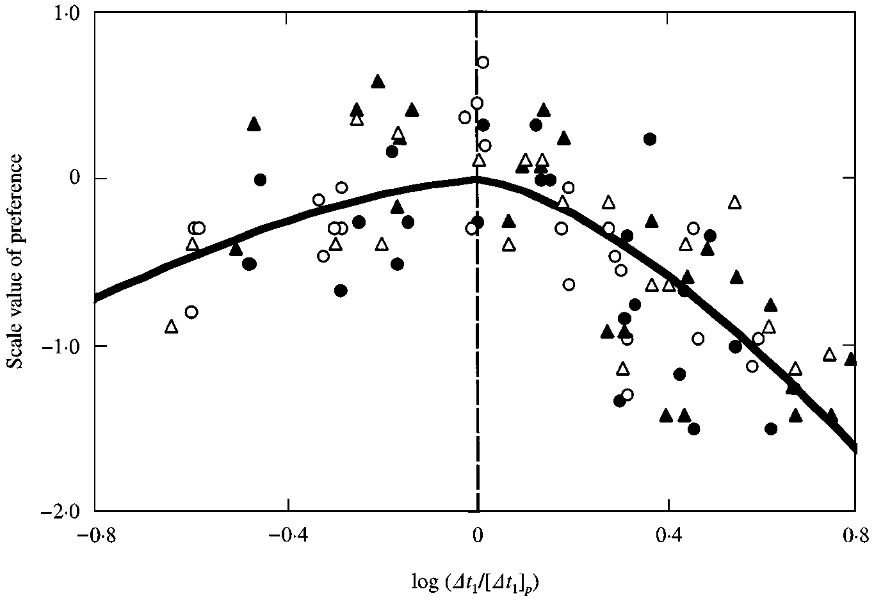

Figure 6. Scale values of preference for each of five cellists as a function of the delay time of a single reflection normalized by its most preferred delay time calculated by equation (4). ●, Music motif I, − 15 dB; ○, music motif I, − 21 dB; ▲, music motif II, − 15 dB; △, music motif II, − 21 dB. The regression curve is expressed by equation (5).

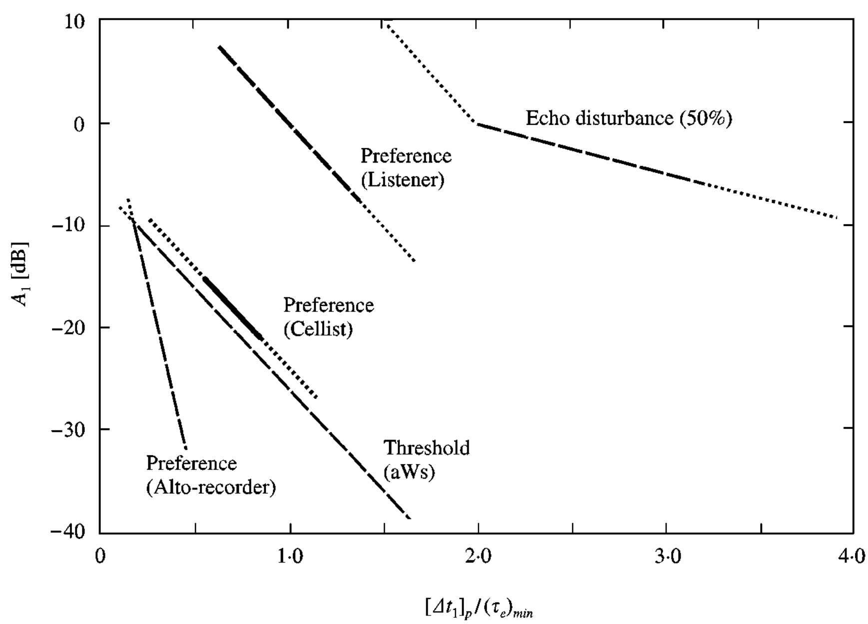

Figure 7. Relative amplitude of a single reflection for the preference of cello-soloists as a function of the delay time of a single reflection normalized by the value of $(\tau_e)_{min}$, as well as several subjective responses as a function of the delay time of a single reflection normalized by the value of τ_e of the source signal [5].

TABLE 5

Optimum distance between the performer and the reflector calculated from equation (4) *in relation to the value of* $(\tau_e)_{min}$ *for the music signal played*

$(\tau_e)_{min}$ of the music signal (ms)	Distance of the reflector (m) Cello soloist						Alto-recorder soloist
	A	B	C	D	E	Averaged	
30	3	10	6	8	4	6	2
50	6	21	13	16	8	13	4
70	9	(33)	21	(26)	13	20	6
90	13	(46)	(30)	(36)	18	(29)	8

Note: the value of τ_e for alto-recorder solosit was obtained for a long time ACF ($2T = 32$ s).

minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF, as well as several subjective responses as a function of the delay time of a single reflection normalized by the value of the effective duration τ_e of the long-time ACF of the source signal. These values can be calculated by equation (4) with constants k and c for each subjective response [5]. The alto-recorder soloist's preference is also plotted in this figure. The values for performers are close to the threshold of perception (aWs) for listeners.

As an application, the delay time of a reflection can be controlled by adjusting the height of the reflectors above the stage. As listed in Table 5, the optimum distance between the performer and the reflector above the stage in relation to the minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of the music program to be performed can be calculated. Here it is assumed that the distance between the instruments and the ear of the performer is 0·6 m for a cello soloist and 0·2 m for an alto-recorder soloist. The height of the reflector above the stage can be adjusted if the minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of the music to be played is measured before the concert. For practical convenience, this adjustment may be made in the real sound field with the subsequent reverberation when the amplitude of a single reflection is replaced by the total amplitude of the reflections.

4. CONCLUSIONS

The most-preferred delay time of a single reflection for each cellist can be calculated from the amplitude of the reflection and the minimum value of the effective duration $(\tau_e)_{min}$ of the running ACF of the music motifs played by each cellist. The scale values of preference for both individual cellists and for global cellists with regard to the delay time of a single reflection can be expressed by a simple formula, normalizing the delay time by the most-preferred delay time observed for different music motifs.

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