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SINGER RESPONSES TO SOUND FIELDS WITH A SIMULATED REFLECTION

D. NOSON

Graduate School of Science and Technology, Kobe University, Kobe 657-8501, *Japan*
BRC Acoustics, 3208 15*th Avenue West*, *Seattle*, *WA* 98113, *U.S.A.*

AND

S. SATO, H. SAKAI AND Y. ANDO

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

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While numerous recent studies have reported results concerning improvements to stage acoustics for orchestral performers, the preferred acoustical conditions on performing stages for singers has received limited attention in the past 20 years. A series of acoustical modifications have been proposed for a Seattle church to improve the acoustics for both the listeners and the performing choir. An on-site preliminary study was made to determine what acoustical changes might be important to singers. During solo fast-tempo singing and duet singing, singer preference increased with simulated short-delay reflections. The results suggest a potential for new reflectors to produce noticeable improvement in the choir acoustics. Subsequently, a solo singer study was conducted to establish preferred range of time delays for a single-simulated reflection. When singing faster-tempo music, the consensus of preference is statistically significant and the preferred delay averages 20 ms, while with a slow-tempo piece, the singers were not consistent in their judgment of preference and a strong individual variability predominated in the pair-comparison tests. The results point the way for an examination of a wider range of time delays and music motifs to acquire a clearer picture of consensus and individual preference for time-delayed reflections.

1. INTRODUCTION

A series of acoustical studies have been conducted over the past five years in the main hall of University Congregational Church, in Seattle. This church, seating about 600, is often engaged for vocal and musical recitals and is the home of one of the most well-respected church choirs in the Seattle metropolitan area. The studies are part of a plan to improve the acoustics of the organ and choir for listeners in the main seating area and for singers and orchestra in the church choir.

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The choir portion of the study, section 2 of this paper, made use of small speakers to simulate revisions to reflections from added or relocated wall and ceiling panels. The investigation sought preliminary indication of the preferred conditions for additional early reflections and will be used to design permanent changes to the acoustical surfaces surrounding the choir.

Numerous acoustical deficiencies have been noted by the choir director and singers, including non-uniform response, a lack of support and difficulties in ensemble blend. In a questionnaire given to over 50 choir singers, most reported that other acoustical environments where they perform have a strong influence on the quality of their singing and a significant effect on their ability to hear each other. It is well known that at very localized places on stage, opera singers have reported strong, positive judgments of superior acoustical response [1].

To establish the independent influences of delay times, as opposed to reverberation or direction of reflections, on singer preferences, the study described in section 3 of this paper examines the subjective response of soloists exposed solely to time-delayed median-plane reflections with delays ranging from 5 to 40 ms and sound level fixed at -3 dB relative to the direct sound from the singer's mouth as measured at either ear.

1.1. PREVIOUS STUDIES OF ACOUSTICS FOR SINGERS

The experimental studies conducted with instrumental musicians by Gade [2], Nakayama [3], and Nakayama and Uehata [4] indicate that strong ceiling reflections are very important both for soloists and ensembles. With singers, however, the listening task is influenced by the act of using the voice as the performing instrument, by the extreme proximity of the voice to the ears, and by internal bone conduction, all of which should influence the judgment of preferred acoustical conditions.

Attempts to determine on-stage singer preference are rare [5, 6]. In the singer ensemble study by Marshall and Meyer in 1985 [6], performing singers were reported to feel most at ease, and were able to hear each other well, when the presence of reverberation was strong, while early reflections provided only a minor, positive effect in the ratings assigned by the singers to simulated sound fields.

In the Marshall and Meyer study, early reflections were set at a relatively low level, compared with the energy level of the subsequent reverberation. The performing environment was simulated in a semi-anechoic room (floor reflections were present) using distributed speakers to produce a reverberant sound field and four delayed reflections, i.e., those from the ceiling, two side walls, and the rear wall. However, there are normally additional early reflections from the junctions of the three walls with the floor and ceiling (6), the rear wall with the side walls (2), and from the four corners of the rear wall, for a total of 12 additional reflections. Had these missing reflections been included in the simulation, the total acoustic energy of early reflections would have been about 6 dB higher.

2. SINGER PREFERENCE FOR CHANGES TO THE ACOUSTICS OF AN EXISTING CHURCH CHOIR

2.1. EXISTING ACOUSTICAL CONDITIONS

To study the response to changes in existing reflecting surfaces, simulated reflections were added to the acoustical environment of an existing performing area (chancel). The reverberation time measured at the choir area, in the empty church, is 1·9 s at mid-frequencies. When the choir is present, the reverberation time drops by 20% or so. The primary reflecting surfaces are located as shown in Figures 1 and 2. The ceiling is 7·5 m above the front section of the floor and the side walls are 10 m apart. The floor is 2 cm thick hardwood over wood sheathing on stiff wood framing and the rear wall is concrete. Side walls, however, are light-weight panels, with widely spaced framing behind. The wall panels are faced with equally spaced vertical wood strips 2 cm wide and 3 cm deep, creating a sound scattering surface.

The church organ is installed on two loft platforms located behind open screens created by an extension of the vertical wood strips from the lower portion of the walls (see Figure 2). The net effect of the scattering side walls, light-weight panels, and open lofts is a diminished level of early reflections. For this reason, simulated reflections were proposed to determine the value of making permanent modifications to strengthen reflections from the chancel surfaces.

2.2. SIMULATION OF SINGLE, ADDED REFLECTION

Singers were asked to perform two short passages, one with a fast tempo, staccato style, and a second at a much slower tempo, legato style. Duets were sung in unison with paired vocal parts — tenors together, likewise for basses, altos, and sopranos. Tempo was rehearsed with an electronic metronome, and a choral leader coached and conducted the singers to stay on tempo.

A single microphone was kept at a distance of 80 cm for soloist and duet singers. The singers, who all sing professionally with local performing arts groups, were trained to sing a sustained vowel at 75 dB(A) (at 1·0 m), and were asked to match their repeated short musical performances to the same level.

Refer to Figures 1 and 2 for the locations of the speakers and microphone. As in the Marshall and Meyer study [6], sound pressure levels for the speakers are set relative to the equivalent distance to the delay of sound from the speakers, so that 10 ms delayed reflections will be 6 dB higher than a 20 ms delayed reflections.

2.3. PREFERENCE RATINGS FROM PAIRED COMPARISONS

The Marshall and Meyer singer study employed a rating scale from 1 to 7, and requested that the singers rate each simulated sound field for “ease in singing” and for “ease of ensemble”. By using a paired comparison method in this study, rather than a point rating scale, the ambiguity about what is meant by “ease” in singing or in ensemble is removed. In addition, the paired comparison method also reduces two additional sources of error: (1) the uncertainty in judging whether a sound field

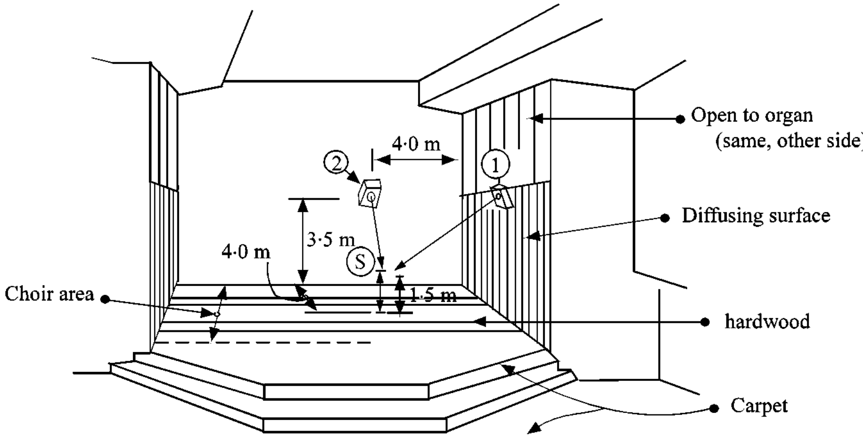

Figure 1. Location of speakers and singer microphone. The singer and microphone, "S", are located 4·0 m from the rear wall and 4·0 m from the left-side wall. The microphone is 1·5 m above the floor. The two speakers, "1" and "2", are 3·5 m above the choir floor.

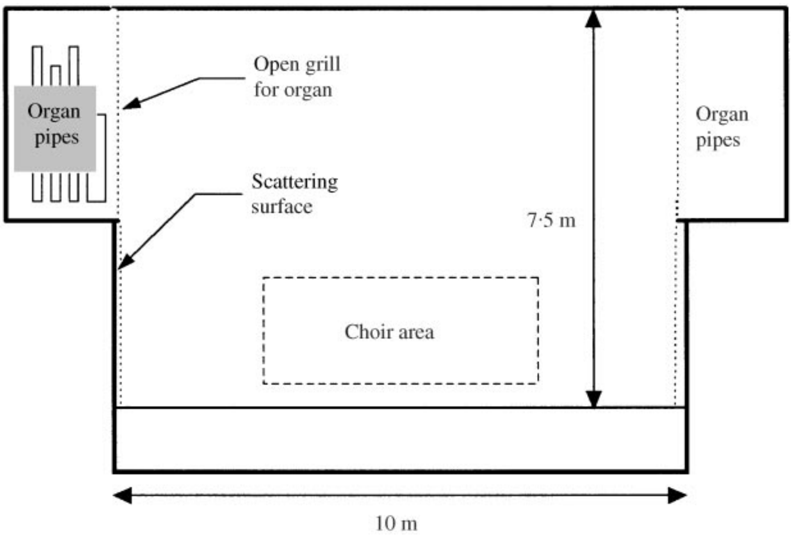

Figure 2. Transverse section through the choir area.

deserves a 3 or 5 rating (absolute judgment errors) and (2) the uncertainty over how well the rating for a sound field presented earlier in the test series is being judged in comparison with the current sound field (relative judgment error).

A total of nine singers were asked, "Which did you prefer?" when presented choir sound fields in pairs and in random order. The preferred condition was scored as $+1$ and otherwise as -1.

Preference scores were added and normalized. A score of 1·0 means complete unanimity of preference judgment for that sound field, 0·0 means an equal number of yes and no scores, and a score of $-1{\cdot}0$ means complete agreement on a lack of preference.

Three categories were examined: (i) solo singers with a time-delayed reflection, (ii) duet singers with a time-delayed reflection, and (iii) solo singers with a left or rear reflection at one of three gains (+ 0, + 6 or 12 dB) relative to the level of a natural reflection. In the first two groups of sound fields, with variable time delay, the singers sang two pieces, one with a fast tempo and one slow. For both pieces, the singers performed solo and in duets. In the third group, the tempo was fast, the delay of the simulated reflection was fixed at 10 ms, and no duets were sung.

Because of time and fatigue constraints with the number of sound field combinations, paired tests were limited in extent, and not all possible pairs were presented. The results are considered to be indications of likely preference trends.

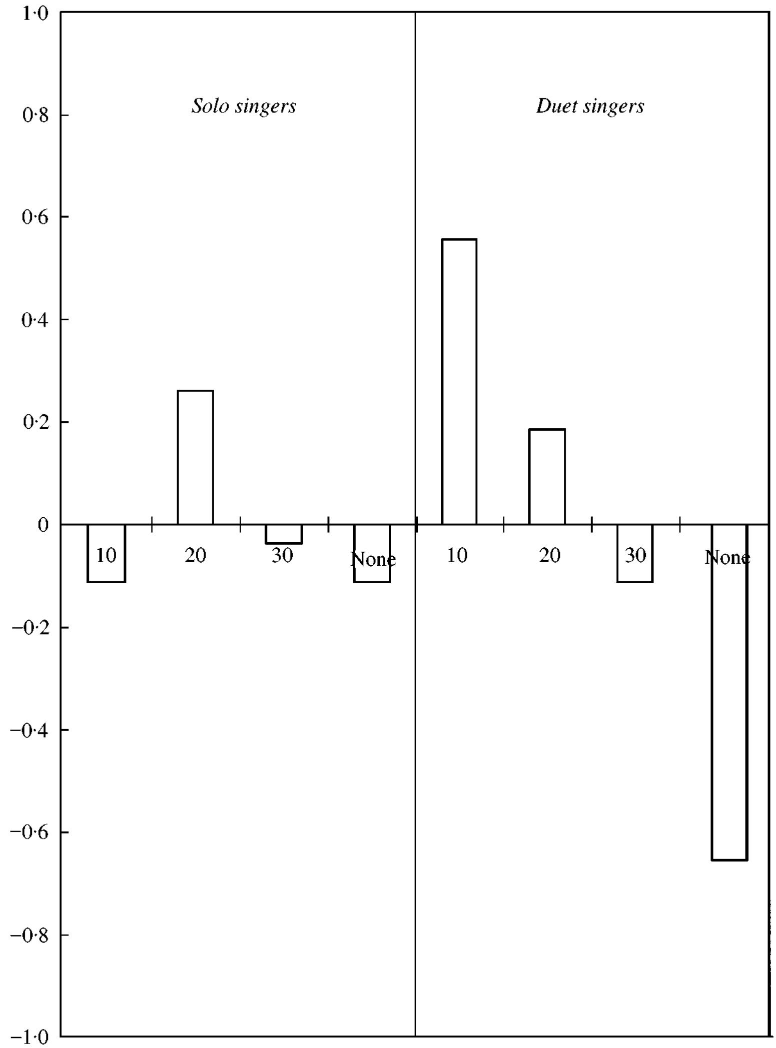

Figure 3. Singer preference scores for sound fields with slow-tempo music. Bars are indicated with the delay time (in ms), of the simulated reflection arriving from speaker "1" (to the left). The bar labelled "None" indicates the case when no simulated reflection was presented to the singers.

Preference studies using fully simulated sound field tests, one of which is reported in the third section of this paper, are in preparation and will include sufficient response data to test the statistical significance of the singer preferences.

2.4. RESULTS OF SINGER PREFERENCE TRIALS

Based on a simple averaging of the comparison scores, the results for variable time delays are shown in Figure 3 and 4, for slow- and fast-tempo music respectively. For solo performance of music with a slow tempo, added reflections had little or no effect on the singer's preference. However, when singing at slow tempo in duets, the individual singers gave a preferential judgment to a single,

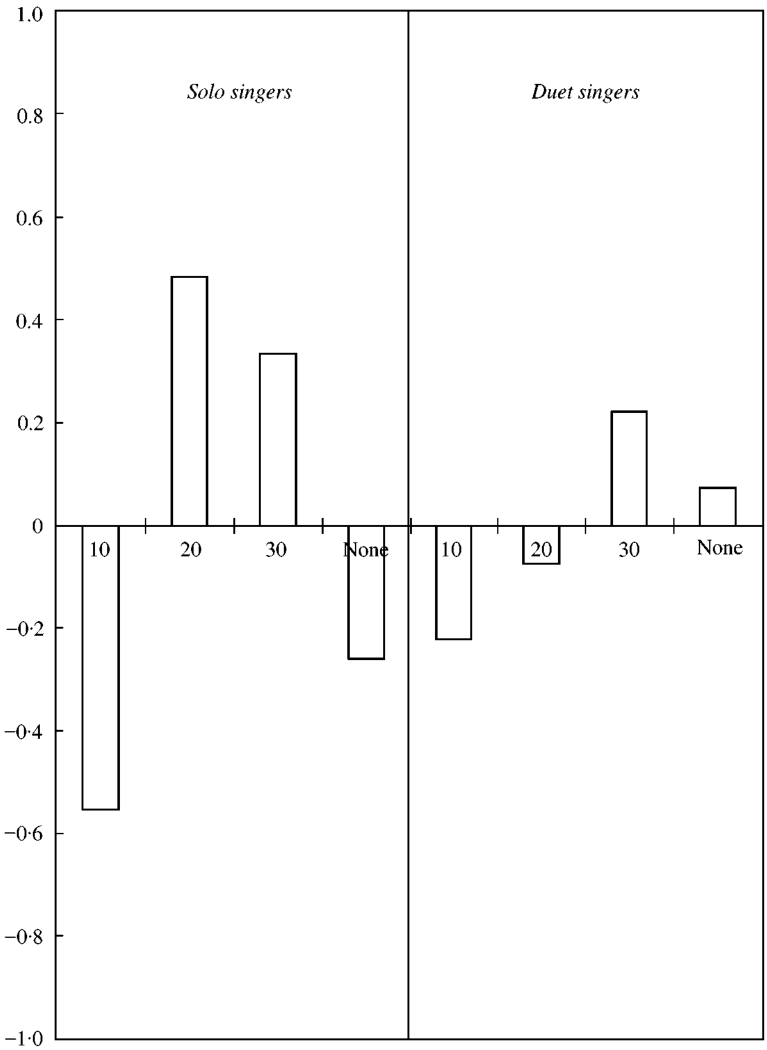

Figure 4. Singer preference scores for sound fields with fast-tempo music. Bars are indicated with the delay time (in ms), of the simulated reflection arriving from speaker "1" (to the left). The bar labelled. "None" indicates the case when no simulated reflection was presented to the singers.

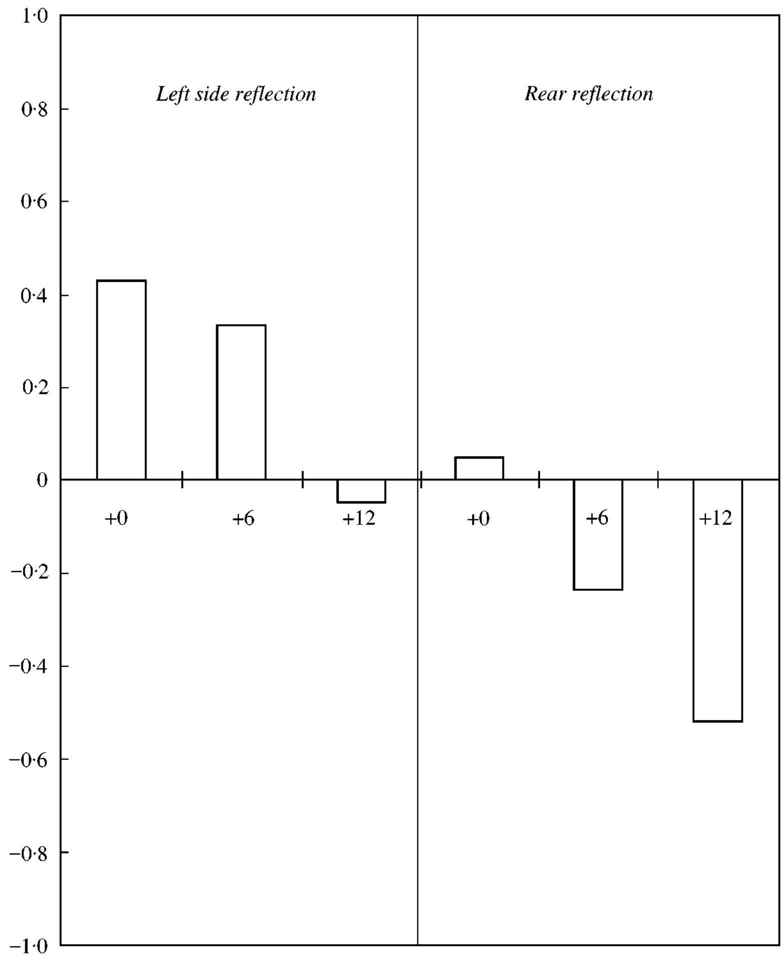

Figure 5. Singer sound field preference for simulated side reflection (speaker "1") and rear reflection (speaker "2"). All conditions were presented in random pairs. The label on each bar indicates the level (in dB) of the simulated reflection relative to the level of a natural reflection arriving from the same distance. Reflection delays were 10 ms.

short-delayed reflection (10 ms). An equally strong *negative* preference was observed for the acoustical conditions when no reflection was added at all.

When fast-tempo music was sung, the situation reversed. Solo singers were now affected by the presence of a simulated reflection, preferring a delay in the range from 20 to 30 ms, while duet singers could not reach a consensus on a preferred delay.

In the third group of paired comparisons conducted with five singers, when reflections at a fixed time delay (10 ms) were presented from the (left) side, singers indicated a positive response (see Figure 5), but not when the simulated reflection was boosted in gain to + 12 dB above its natural level. When compared with 10 ms delayed reflection in the medial plane, a + 12 dB medial-plane reflection appears strongly not to be preferred relative to side reflections.

3. PREFERENCE STUDY OF SINGLE-DELAYED REFLECTIONS

3.1. STUDY PROCEDURE

A single reflection was presented to singers in a small anechoic chamber. The speaker was located 1·0 m behind each singer and reproduced the voice of the singer from a headset microphone located approximately 10 cm in front and 5 cm below the singers mouth (see Figure 6).

Another microphone located at the right ear canal entrance was used, prior to the paired comparison trials, to set the level of the simulated reflection at -3 dB relative to the sound of the singing voice arriving directly from the singer's mouth to the ear. This level was chosen based on the response of the singers when asked what level represented a noticeable change to the response of the room, as simulated by the speaker-delayed signal. The singers voice level was again trained at 75–80 dB(A) according to the comfort of the individual singer's vocal effort (moderate effort).

Figure 6. Singer subject C, with microphone headset.

This reflection was then delayed by 5, 10, 20, or 40 ms, and presented in random ordered pairs for the singer's paired comparison of preference. The singers again sang either a slow or fast-tempo piece, using the same music motifs from the previous church study. The singers performed only as soloists in this study.

Six pairs were presented at each session, and the singers repeated the sessions five times. Each session required 2·5–3 min and the order of pairs was randomized between sessions. Using the method of Ando and Singh [7], scale values of preference for each of the four sound fields were determined for the individual singers and music motifs. Statistical tests for consistency and agreement were also applied to assess the validity of the scale value determination. From the scale values, for some singers, it was possible to determine their preferred time delay using a curve fitting procedure.

3.2. RESULTS

As with the church study, when singing the slow-tempo piece, the singers were inconsistent in their preferences for the delayed reflection. Figure 7 shows the scale value of preference for the slow-tempo music, with good consistency results only for singer subjects B and D. No clear delay time preference can be discerned, but,

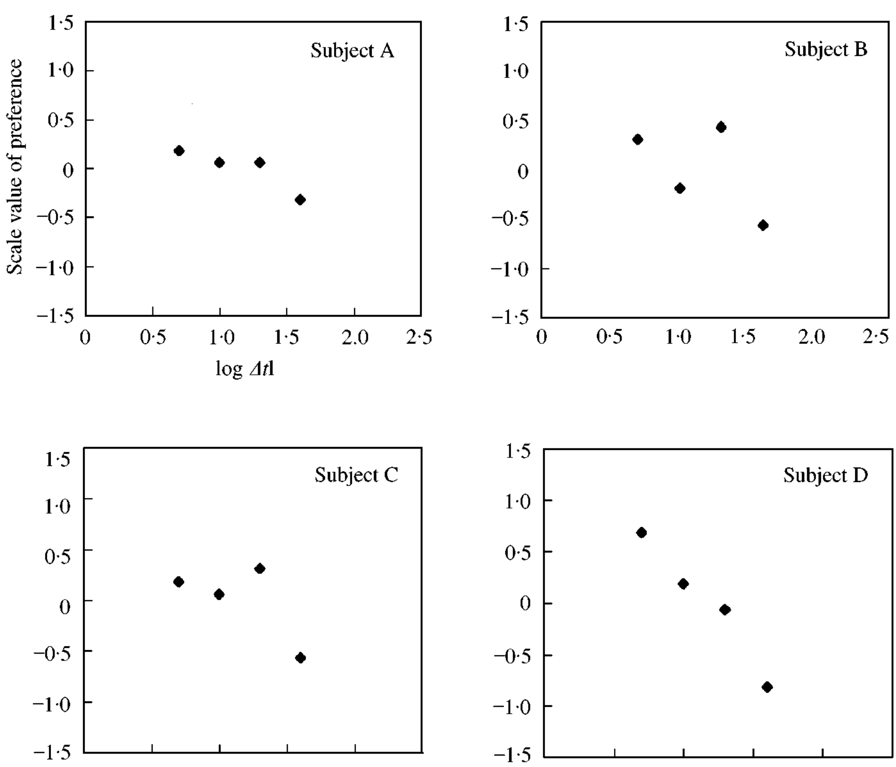

Figure 7. Scale value of preference for each singer with slow-tempo music. Four subjective scale values corresponding to preference tests for each of four time delays: 5, 10, 20 and 40 m.

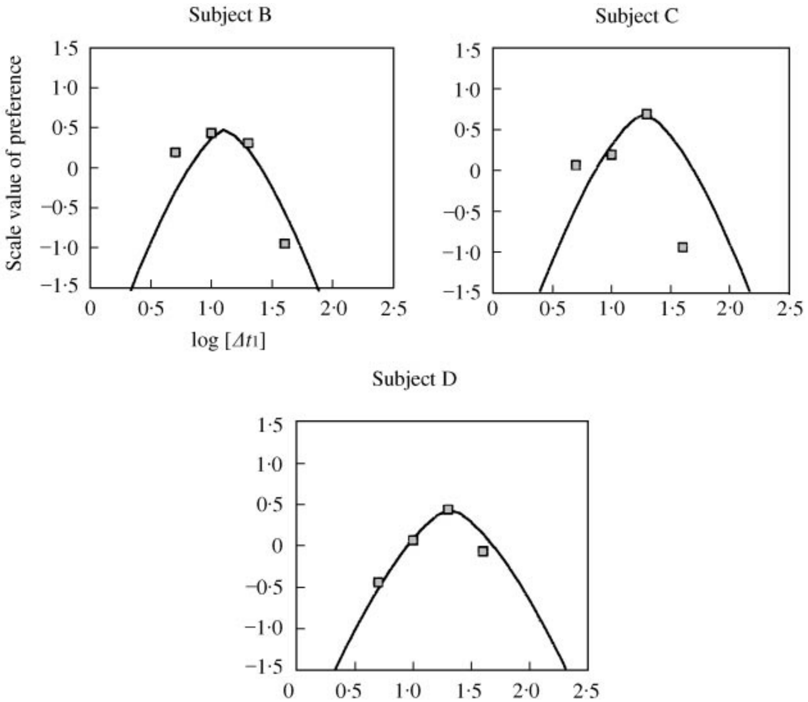

Figure 8. Regression curve fitted to subjective scale values with fast-tempo music. Four subjective scale values corresponding to preference tests for each at four time delays. 5, 10, 20 and 40 m.

instead, the results suggest a monotonically declining preference with larger delay times.

For fast-tempo music, tests of consistency and agreement were higher, and the apparent trends in preferences are therefore more reliable than with the slow-tempo motif. Figure 8 shows the scale values of preference for the fast-tempo music. The data of the paired tests from singer subject A were not consistent and were ignored. Regression curve fitting for the scale values with fast-tempo singing are also shown in Figure 8. The peak value of the preference results is the preferred delay time of the reflections, for each singer, and is obtained from the peak of the regression curves, as follows: singer B, 13 ms, singer C, 19 ms, and singer D, 21 ms, average 17·5 ms.

3.3. MINIMUM RUNNING ACF

The preferred time delay can be interpreted in the framework of Ando's subjective preference theory for listeners and performers. One component of Ando's theory [8, chapter 4] states that the preferred delay time is directly dependent upon the temporal characteristics of the sound source, as measured by the effective duration of the autocorrelation function (ACF). The effective duration of the ACF is symbolized as τ_e. The value of τ_e may be calculated from recordings of individual singer's or musician's performances. Minimum levels of the running calculation of the ACF are a representative measure of the most critical listening task during the

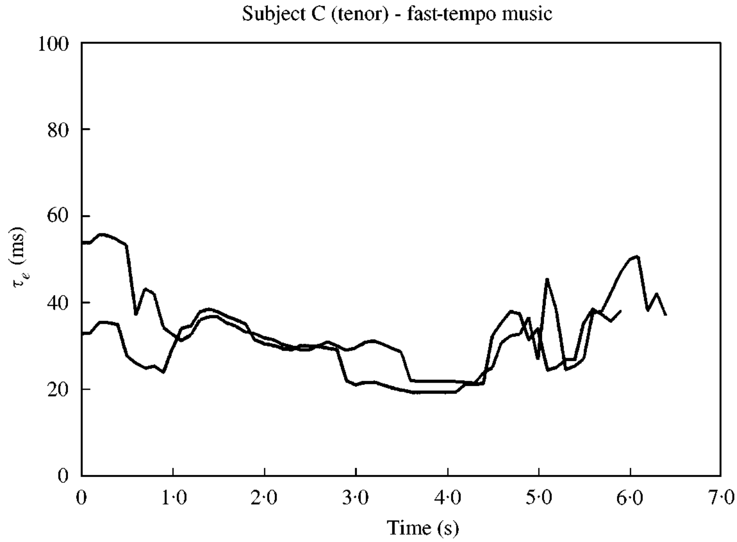

Figure 9. Sample of running calculation of the effective ACF, τ_e (for singer subject C). Two recorded performances are shown ...., 1st; ——, 2nd.

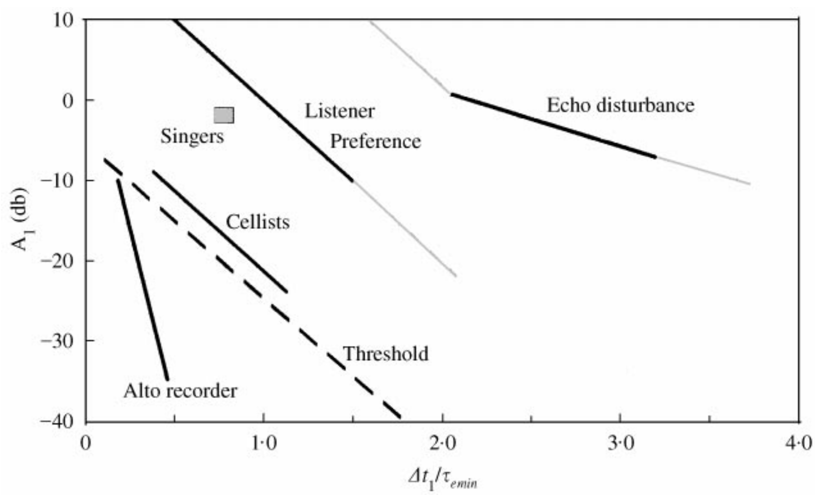

Figure 10. Singer's preferred reflection level, while performing, for sound fields with a single reflection. The single reflection is delayed by Δt_1. The delay time is normalized by the effective duration of the ACF, τ_e, of the performed music or speech. Singer results were obtained over a limited range of $\Delta t_1/\tau_e$ and are therefore limited to a small range, in comparison with results for cellists, alto recordists, and listeners.

performance of a musical phrase [9]. A sample of the minimum running ACF ($(\tau_e)_{min}$) calculation of slow-tempo music for singer C is shown in Figure 9.

For singers B–D, with statistically reliable fast-tempo scale values, the minimum running ACF values were calculated from two anechoic samples for each singer, performing the fast-tempo piece. The values are 16, 22 and 18 ms, respectively, indicating a nearly direct correspondence between preferred delay time (13, 19 and 21) and the tempo and performing style of the musical passage.

A linear relationship between reflection level (in dB) and the ratio of the preferred time delay to minimum running ACF has been proposed as a means for comparing the listening tasks of performers in single-delayed reflection sound fields [8]. The result for singers is these two studies has a limited range of $(\tau_e)_{min}$ and therefore a linear relationship has not been demonstrated. However, the results, plotted as a point in Figure 10, indicate a singer preference close to the preference relationship for listeners. The -3 dB reflection level of this study places singer's preferences at a relatively higher reflection level than cellists [10] or alto recorder performers.

4. DISCUSSION

The results of both the church and simulation room studies indicate that singers were not able to form a stable assessment of a slow-tempo piece with a variable time-delay sound field comparison.

The nearly equal preferred time delays and minimum ACF values of 15–20 ms, which were observed for a -3 dB reflection level, suggests that the high levels of masking of direct sound from the voice's proximity to the ear or bone conduction (or both) causes a shift in the preferred time delay of reflections to longer delays than have been observed as preferred by instrumental performers. Further study of this question is planned by extending the range of time delays and by selecting alternate music motifs with higher minimum values of the running ACF.

The limited data available from the side reflection study in the church makes a firm conclusion unreliable, but the result is suggestive of a potential value for side reflections. Further study of the effect of side reflection is also needed to established the validity of the observed preference for side reflections.

A greater body of statistically valid singer preference data, for reflection delay times and directional angles as well scale values of singer preference for reverberation, will provide a basis for optimizing stage configurations to suit individual performers.

5. SUMMARY

In solo singing, an added reflection elicited the highest singer preference when performing fast-tempo music (in both studies), but for slow-tempo music, added reflections showed little effect on a singer's judgment or, as shown in the study of section 3, singer preferences tended to decrease with longer delays of the added reflection. With duet singers, at fast tempo, a preferred delay was not apparent.

For slow-tempo *duet* singing, however, the church study suggests that the presence of an added reflection was preferred over no reflection at all.

The anechoic simulation study resulted in a statistically reliable set of subjective scale values for three singers, with a mean preferred time delay of 17 ms for a fast-tempo music motif, characterized by a minimum running ACF of 15–20 ms.

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