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THE SUBJECTIVE EFFECTS OF FIRST REFLECTIONS IN CONCERT HALLS—THE NEED FOR LATERAL REFLECTIONS

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This paper describes experiments with simulated reflections in an anechoic chamber, in an attempt to understand the importance of early reflections in a concert hall. The subjective effects of a single side reflection were investigated; and the effect of "spatial impression" was identified as the predominant subjective effect. This "spatial impression" was produced for reflection delays between 10 and 80 msec by lateral rather than ceiling reflections.

The variation in the degree of spatial impression for variations in different reflection parameters was investigated, as was the effect of two side reflections. It was concluded that the degree of spatial impression is probably related to the ratio of lateral to non-lateral sound arriving within 80 msec of the direct sound. Other authors' theories of the role of first reflections are discussed in the final sections of the paper. Results here gave support to the view that a cross-correlation process is involved in subjective spatial impression.

1. INTRODUCTION

It is widely accepted that reverberation time is not the only determinant of acoustical quality in a concert hall. Many investigators have turned their attention towards the early reflection sequence in the hope of finding further objective measures which correlate with subjectively audible qualities. As reflection sequences in real halls are highly complex and difficult to alter for experimental purposes, experiments with simulated reflections offer a much more flexible means of gaining an understanding of the role of first reflections.

The first simulation experiment was conducted in 1950 by Haas [1], who investigated the effect of single short-delay reflections with speech. As a result of further investigation with speech by others, the relation between early reflections and speech intelligibility is now well understood. Relatively little progress, however, has yet been made for the case of early reflections with music to explain their subjective significance.

It is the aim of any work on subjective concert hall acoustics to discover subjectively audible qualities in real halls and ultimately to derive design criteria for halls to produce optimum degrees of these subjective qualities (if this is in fact possible). There are many steps involved in such investigations, especially if simulation techniques are used. This paper will concentrate on the subjective aspects of first reflections, simulated in an anechoic chamber. In particular, it will deal with the relation between the physical properties of reflection sequences and the subjective effects produced. While occasional comments relevant to concert hall design are made in the concluding sections, it is hoped at a later date to make a fuller investigation of the physical acoustic aspects of the problem.

The unusual arrangement of this paper deserves explanation. The experimental results are discussed in three sections: section 3 which contains threshold results, section 4 which describes qualitatively the subjective effects of a single side reflection and section 5. The two

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former sections can be considered as preparatory to section 5. In section 3 it is asserted that threshold results can not be used for above-threshold predictions, and from section 4 besides loudness effects "spatial impression" is isolated as the only positive subjective contribution of first reflections to sound quality. Section 5 describes a quantitative investigation of "spatial impression". In section 6 there is a discussion of the results of section 5 relative to other authors' experience.

1.1. HOW FAR CAN WE SIMPLIFY THE PROBLEM?

The number of possible reflection sequences in reality is infinite. Careful consideration should therefore be made of the most valuable situations to study. Other experimenters' results, also confirmed here, have shown that the sound arriving at the listener's ears within about the first 100 msec after the direct sound makes a contribution different from that of reverberation. The sound arriving within the first 100 msec will consist of primary reflections, reflected from the side walls, the ceiling and orchestra enclosure, and higher order reflections. Seraphim [2, 3] has found that for speech the maximum number of perceptible early reflections in a real hall is about 15. As, in general, thresholds for music are higher than they are for speech, this result can be used as an upper limit for investigations with music. However, due to spherical divergence of sound, the earliest reflections will have the highest intensity and are thus likely to be the most significant.

The clearest representation of a reflection sequence in a real hall is in the form of an "echogram"—an impulse response displayed on a CRO. Looking at a series of "echograms" of a concert hall (e.g. in [4]), one is struck both by their complexity as well as the extreme variation for different points in the hall. Even an "echogram" however does not include all the information; each reflection is described by at least four dimensions: level, delay and two for direction. The proportion of all possible situations with even only two or three reflections that we can investigate is of necessity very small.

To understand the role of first reflections, it was decided to investigate the simplest situation first: that of a single reflection, and to obtain an adequate understanding of the factors involved in preparation for interpreting more complex situations. This approach proceeds from the assumption that the ear reacts to simple situations as it does to complex; i.e. that the effects of many reflections are summated. The validity of this assumption in the cases studied should become evident as we proceed.

2. EXPERIMENTAL DETAILS

2.1. PROCEDURE

Of all forms of subjective judgment expressed in words, that of acoustical quality is one of the most elusive. One approach, which makes the minimum number of prior assumptions, is to employ a questionnaire technique requiring large numbers of subjects. However with simulation experiments it is possible to use a more direct approach: to state the subjective effect one expects a subject to observe, and to ask him to compare the degree of this effect between two situations. For instance, to discover factors determining loudness, one can ask a subject to compare two situations and determine which is the louder. It is perhaps surprising that this is possible with simulated reflection sequences; the effects produced by adding a reflection can however be described simply. One can, with surprising accuracy, compare two acoustical situations with regard to a single subjective effect, by arranging an experiment so that the number of subjectively perceived variations is a minimum (something which is easy in some experiments and very difficult in others). Two forms of quantitative experiment were conducted: threshold measurement, described at the beginning of section 3, and a comparison technique described under section 5.

In using these methods a certain amount of oversimplification is inevitable, but such methods offer a rapid means of obtaining results which are then open to verification by more rigorous techniques. The self-testing procedure was chosen as the most appropriate for this sort of experiment, as this was both highly convenient for setting-up, and demanded the shortest subject time.

2.2. APPARATUS

Figure 1 is a diagram of the test set-up with the switching arrangement as for the experiment described in section 5.1.1. Music motifs, recorded on tape loops, were played on a conventional tape recorder. The output signal was then fed into a Leevers–Rich tape-delay apparatus which produced four outputs, which could be delayed at will relative to one another (the representation in Figure 1 is purely diagrammatic, there were in fact four independent
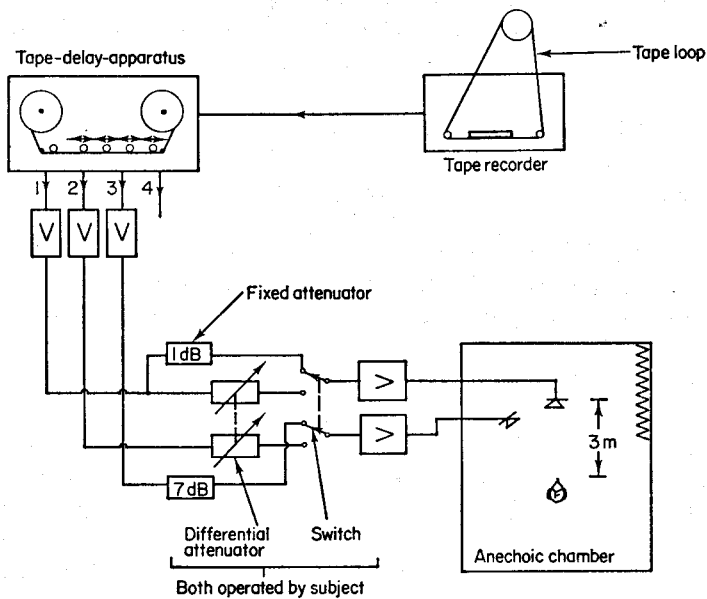

Figure 1. Test set-up (as for experiment described in section 5.1.1).

record-replay channels). The signals then passed through an impedance matching device to attenuators and switches in the anechoic chamber for the subject to control. After further amplification the signals were played in the anechoic chamber through Quad electrostatic loudspeakers (chosen for their good frequency and impulse response). The subject was placed in a chair at the centre of the loudspeaker array; subjects were asked to face directly forwards, but no physical restriction was placed on head movement. One loudspeaker (straight ahead) corresponded to the direct sound. At most three other speakers produced reflections from varying directions; all these speakers were arranged at 3 m from the subject's head.

A reverberant field was also included in certain sections of the experiment. A recording was made on a second channel of the tape loop from a reverberation plate. The reverberant signal was delayed about 100 msec relative to the direct sound, as is common practice in broadcasting. By using a delay of 100 msec, the reverberation did not overlap the discrete reflections which were being studied. The reverberation was played through four loudspeakers placed symmetrically about the subject's head, but arranged to produce temporal incoherence, as described by Meyer, Burgtorf and Damaske [5]: one pair of loudspeakers, opposite one

another, were placed about 40 cm further from the subject's head than the other pair to introduce a time delay difference between the two reverberant signals. The sound levels of the pairs of loudspeakers were adjusted to compensate for the difference in distance. Ordinary paper-cone loudspeakers were considered adequate for the reverberation; they were placed at the same height as the subject's ears.

Each experiment used a different switching arrangement, though in each case the principle was the same as in Figure 1 with the subject in control of a switch and an attenuator. Because experiments were designed to study effects other than loudness changes, the incoherent sum of the levels of the sound components was kept constant throughout the experiment. To fulfil this condition a differential attenuator was used for the subject to operate, so that while the reflection level relative to the direct sound was altered, the total level remained constant. The mean level at which music motifs were played to subjects will be referred to as E dB relative to 0·0002 dyne/cm^2.

To obtain the correct delays for reflections, pure tones were fed into the tape-delay apparatus and the phases of the output signals from it were compared at different pure tone frequencies. The accuracy of the stated delay was better than 0·5 msec. Before each experiment a microphone was placed in the position of the subject's head and the level of each reflection was adjusted using a 1 kHz signal. A pure tone was chosen for this in preference to noise since the loudspeaker responses were flat around that frequency, and pure tones permitted more accurate adjustment.

2.3. NOTATION

The angle of azimuth (lateral direction) will be represented by the symbol α, measured in degrees anticlockwise from straight ahead; $\alpha = 90°$ is therefore on the subject's left. The angle of elevation (vertical direction) will be represented by β, measured in degrees above straight ahead; $\beta = 90°$ is therefore directly above the subject's head. For clarity the following notation will be adopted to describe the four dimensions of a reflection: (level, delay, azimuth, elevation). The reflection level is that relative to the (incoherent) *sum* of the levels of the direct sound plus early reflections, E dB. The delay is that relative to the direct sound. The direct sound and the lateral reflections came from loudspeakers placed at ground level, which corresponded to an elevation of $\beta = -16°$; this is, however, a typical angle for modern raked-seating concert halls. Thus (0 dB, 0 msec, 0°, −16°) would refer to the direct sound as in a threshold experiment, in which the direct sound is of absolute level E dB. Similarly (−7 dB, 40 msec, 40°, −16°) refers to a side reflection delayed 40 msec, −7 dB relative to the level E dB.

2.4. MUSIC MOTIFS

The motif used for the majority of the experiments was a 47 sec section of the 4th movement of Mozart's Jupiter Symphony (No. 41), bars 94–151, recorded by the English Chamber Orchestra in the Building Research Station anechoic chamber. The section is a typical example of fast classical music, it has a wide dynamic range and contains most instruments of the orchestra.

For two of the experiments (those conducted first) a 30 sec motif from Vivaldi's Concerto for two violins in B minor was used. This section was not as purely anechoic as the Mozart motif, but was the only section of non-reverberant music available at the time.

For each experiment the sound level E was set up to be the most natural subjectively.

2.5. SUBJECTS

Initial experience with threshold measurements soon indicated that the most suitable subjects were those who were both used to listening to music and had some experience of audiological tests. A degree of training was also found necessary, subjects did at least two

experimental sessions before their results were used. Although the number of subjects used was small, the variations between subjects thus chosen was smaller than expected. Other experimenters in the same field (e.g. Schubert [6]) have also found that using small numbers of subjects was valid.

3. THRESHOLD RESULTS

As initial experiments with the apparatus, three threshold measurements were made: the threshold of a single side reflection, the threshold of a ceiling reflection, and the threshold of a side reflection in the presence of a ceiling reflection. Subjects were asked to adjust an attenuator in 1 dB steps until the presence of the reflection could no longer be detected. For reference, subjects could switch off the test reflection signal completely.

3.1. THRESHOLD OF A SINGLE SIDE REFLECTION

The threshold of a single side reflection (azimuth $\alpha = 40°$) was measured by two subjects with the Mozart motif at a mean level $E = 81$ dB. The mean results of the threshold plotted against delay are shown in Figure 2. The intersubject differences were never more than 3 dB.
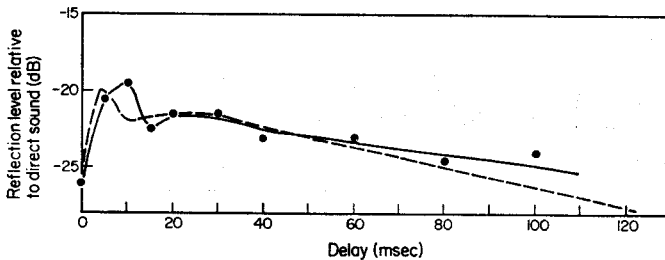
Figure 2. Threshold of a single side reflection for music. ●———●, Threshold for Mozart motif for reflection, $\alpha = 40°$; ————, threshold (after Schubert) for "choral" motif for reflection, $\alpha = 30°$.

The corresponding result of Schubert [6] (from his Abb. 8) for the case $\alpha = 30°$ for a choral motif is also plotted in Figure 2—the agreement is surprisingly good. The minor qualitative differences (that the first peak occurs for a different delay, and that the slope for long delays is different) are fully explained by the difference in motif; Schubert's Abb. 2 shows similar variations between motifs.

3.2. THRESHOLD OF A CEILING REFLECTION

The threshold of a single ceiling reflection at $\alpha = 0°$, $\beta = 40°$ was measured by two subjects with the Mozart motif. The result was within 0 to −2 dB of that for a side reflection in Figure 2 (except for 0 msec delay where it was −22 dB relative to the direct sound). This threshold is on average 6 dB lower than Schubert's [6] for his motif 2 with direct sound and reflection in the same direction (shown in his Abb. 2). Schubert's signals were adjacent while ours were widely separated; he claims, however, that the variation in threshold for music is practically insignificant for changes in elevation. This phenomenon will have to be investigated further.

3.3. THRESHOLD OF A SINGLE SIDE REFLECTION WITH A CEILING REFLECTION PRESENT

With the *Vivaldi* motif at a mean level $E = 72$ dB, three subjects were used to determine the threshold of a single side reflection ($\alpha = 40°$) in the presence of a direct sound (−2 dB, 0 msec, 0°, −16°) and a ceiling reflection (−4 dB, x msec, 0°, 40°). The threshold result with the ceiling reflection delayed $x = 37$ msec is shown in Figure 3; the threshold (relative to direct sound at 0 dB) of the side reflection with only the direct sound present (Vivaldi motif) is also included.

Intersubject differences in the ceiling reflection case were $\leqslant 6$ dB. Results for different ceiling delays were similar.

The threshold of a single side reflection relative to direct sound and fixed delay reflection has been extensively investigated by Seraphim [2,3] for the case of speech. Seraphim's result [2] in his Bild 4(c), for direct and fixed delay reflection from straight ahead and test reflection at $\alpha = 30°$ is presented here in Figure 4; the corresponding threshold with only a direct sound from Seraphim's Bild 2 is also included.

While our result is not statistically substantiated, the similarity in form of the speech and music results is instructive. In both, the gradients of the two *forms* of threshold, with and without fixed delay reflection, are very similar; for speech it is 0·5 dB/msec, for music 0·1 dB/msec; Seraphim's results show that the threshold after the 40 msec delay reflection is similar to that after the direct sound. Similar results were obtained for music as shown in Figure 3. Seraphim
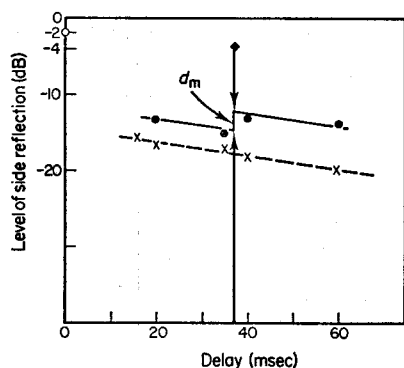

Figure 3. Threshold of side reflection with direct sound and ceiling reflection (delay 37 msec) for music (Vivaldi). ×---×, Threshold with direct sound only.
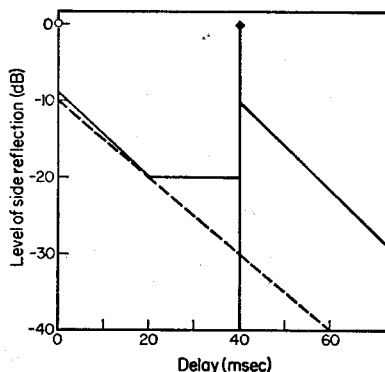
Figure 4. Threshold, as in Figure 3, with 40 msec fixed reflection for speech (after Seraphim). ----, Threshold with direct sound only.

found that this form of threshold occurs when the test reflection arrived from a direction outside the angle included by the direct sound and fixed reflection. However, the difference in gradients for the cases of speech and music means that the threshold shift, when the 37 msec reflection (or 40 msec for speech) is added, is much smaller in the case of music. Also the *change* in threshold as the delay increases through that of the ceiling reflection, d_m in Figure 3, is small for music.

3.4. CONCLUSIONS

The threshold results for a single side reflection agree well with Schubert's results [6]. The results for a ceiling reflection agree qualitatively with Schubert's but the actual threshold curve lies about 6 dB lower than his. The threshold for a side reflection in the presence of a ceiling reflection agrees well in form with Seraphim's results [2, 3] for speech, with the important difference that the gradient of threshold curves is lower for music than it is for speech.

Because of the relative "objectiveness" of threshold measurements, it is tempting to infer properties of perceptible reflections from threshold results. This is, however, seldom valid, as threshold behaviour is only a limiting case of the above-threshold behaviour. While it may be possible to explain threshold behaviour in the light of above-threshold experience, to argue from threshold experience to the general case is to suggest that thresholds are determined solely on the basis of one subjective effect. An example to support this argument is

seen in Figure 5 discussed in the next section, the threshold curve appears to be related to the domains for the various subjective effects, but to have made predictions on the basis of threshold results alone would be totally erroneous. For this reason the threshold will for the remainder of this paper only be used as a base line for the investigation of perceptible reflections.
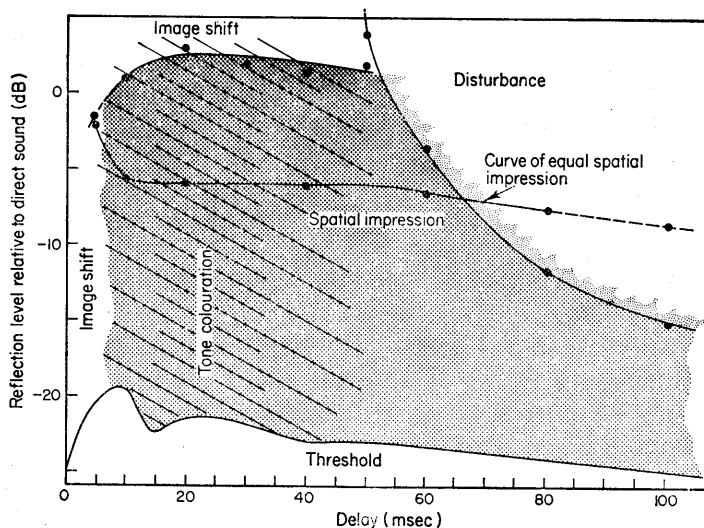

Figure 5. Subjective effects of a single side reflection ($\alpha = 40°$) of variable delay and level using music.

4. SUBJECTIVE EFFECTS PRODUCED BY A SINGLE SIDE REFLECTION

An investigation was made of the effect produced by a single side reflection at $\alpha = 40°$ for different delays and levels. The following effects were observed: level change, localization effects, tone colouration, echo disturbance and spatial impression.

It is generally accepted that the ear integrates the incident energy as a ballistic instrument with a certain time constant. Using intelligibility tests, Lochner and Burger [7], have established that for speech the time constant is about 30 msec, though it depends on reflected/direct level. Niese [8] has obtained a value of 23 msec using tone pulses. No experimental determination has yet been made, however, of the time constant for music, but a value of 50 msec is usually assumed. This means that the addition of an early reflection will increase the subjective loudness. For this reason, to enable subjects to concentrate on effects other than loudness changes, experiments were conducted so that the incoherent sum of the signal levels remained constant.

To determine the subjective effects of a single side reflection, subjects were presented with different delay reflections and were able to adjust the differential attenuator for themselves in 1 dB steps, to change the reflection level relative to the direct sound. First the general qualitative effects of a side reflection were established through consultation between subjects. Then the subjects were asked to determine for themselves the maximum or minimum delays and levels at which the various effects occurred. Because the transition from one effect to another is a gradual one, the results are not more accurate than ± 3 dB (the threshold curve and the curve of equal spatial impression are exceptions to this statement; a different experimental technique was used for their determination). The Mozart motif was used at a mean level of $E = 77$ dB. The results shown are the average of two subjects.

Figure 5 summarizes the effects observed. A description of each section of the figure is included below. The results in this figure can be compared with a one-dimensional version of the same diagram in Tabelle 2 of Schubert [6].

4.1.1. *Threshold*

As a base line for the effects of a side reflection, the threshold from Figure 2 is included in Figure 5; reflections below threshold produce no audible effect. The threshold line and all other solid lines in Figure 5 represent lines of equal subjective impression.

4.1.2. *Localization effects*

It was found that, in general, one localizes on the direct sound; an observation originally made by Haas [1]. However, in the extreme situation of a very short delay reflection (< 5 msec) or a high level reflection with delay less than 50 msec, the apparent source moved from the direct sound loudspeaker towards the reflection loudspeaker. The effect is very similar to that observed when the balance control of a stereo system is adjusted. This movement of the point of localization is indicated in Figure 5 by the unshaded areas marked "image shift".

4.1.3. *Tone colouration*

For certain delay reflections (from about 10–50 msec, but especially around 20 msec), the tone of the music appeared to sharpen, especially the violin tone. The degree of colouration was, however, relatively independent of level for reflections more than 10 dB above threshold. This tone colouration is indicated in Figure 5 by diagonal-line shading, the density of the shading roughly corresponding to the degree of colouration.
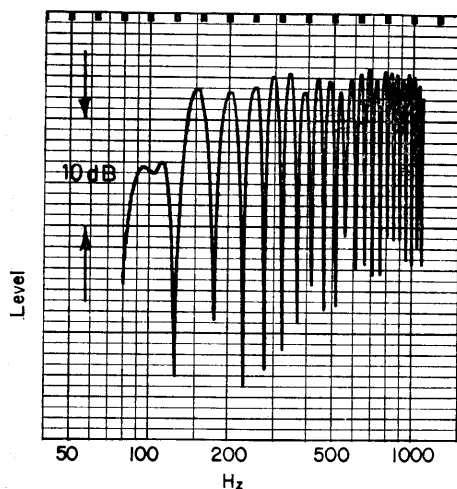

Figure 6. Frequency response of a signal plus 20 msec delayed reflection.

One explanation of this colouration effect is the interference effect between a signal and a delayed version of itself, producing a comb filter. Figure 6 shows a comb-filter frequency response of a signal plus a 20 msec delayed reflection. This was obtained by feeding the signal from a Brüel and Kjær oscillator type 1022 into the experimental arrangement in place of the music signal. For the sound from the *two* loudspeakers a conventional loudspeaker response was taken with a microphone placed in the position of a subject's head. The response in Figure 6 is for the signal and reflection at equal sound level.

Similar observations, recorded later in this paper, on colouration produced by ceiling reflections strongly suggest that colouration is a monaural effect. The effect becomes less noticeable as the direct sound and reflection sources are separated laterally.

Müller [9] has explained colouration in terms of a residual-tone effect. The repetition pitch cannot however explain shrill tone for reflections with a delay greater than 20 msec. He adds:

"Short delay reflections with music can cause melodic as well as harmonic distortions. ... (Colouration) is particularly prominent with broad band spectra, with heavy instrumentation and especially with percussion instruments." (Müller—author's translation.)

4.1.4. *Echo disturbances*

High level reflections of delay > 50 msec became disturbing; as the delay increased the level at which they first became disturbing decreased. The onset of disturbance was determined by the two subjects; the average results are included in Figure 5 as a curved solid line, passing through the four experimentally determined points. The result is similar to that of Muncey, Nickson and Dubout [10] with fast string music using a larger number of trained subjects. Muncey *et al.* found, however, that the disturbance limit also depended on music tempo.

It should be mentioned here that with echo disturbance the effects of many reflections are *not* summated. The following references to this effect deserve mention: Meyer and Kuhl [11] who observed that the degree of disturbance produced by a reflection of delay, say between 50 and 100 msec, will be much reduced by adding a preceding reflection. Also according to Nickson, Muncey and Dubout [12] and a theoretical investigation by Niese [8], the onset of disturbance in the more general reverberant case is considerably affected by the reverberation time.

4.1.5. *Spatial impression*

None of the effects of a single side reflection so far mentioned constitute a significant positive contribution to the sound quality; tone colouration, for example, with a side reflection is both negative and will frequently be masked in a complex reflection sequence, echo disturbance is also a negative contribution, etc.

It was found that, for the majority of reflection situations, the subjective effect of a side reflection was "spatial impression", it occurs for all delays > 10 msec. When, for example, one increased the level of a 40 msec delay side reflection from threshold, the source appeared to broaden, the music beginning to gain body and fullness. One had the impression of being in a three-dimensional space. As the reflection level was increased, the amount of source broadening also increased, until for high echo levels there was an image shift. This broadening effect or spatial impression was easy to appreciate; subjects in fact found it relatively easy to equate two spatial impressions.

The dominant shaded area in Figure 5 indicates the extent of "spatial impression". The density of the shading is varied simply to indicate that the degree of "spatial impression" increases as the reflection level rises.

Other authors [6], [13], [18], [19], [21] have also noted this desirable effect produced by early lateral reflections in concert halls, calling it "spatial responsiveness", "ambience", etc. Marshall [13] includes a good description of spatial impression from the Manager of the Concertgebouw Orchestra of Amsterdam, who described it as the difference between feeling *inside* the music and looking *at* it, as through a window. The impression is however very different from that produced by reverberation; the latter tends to remove the starkness of anechoic music, providing a certain degree of envelopment in the sound and giving an impression of distance from the source.

This binaural impression will here be called "spatial impression" (corresponding to the German "Raumeindruck"), though the author is fully aware that reverberation also produces a different form of room or spatial impression. In the absence of any agreement between other authors of a suitable term, the term "spatial impression" (SI) does at least convey its binaural and subjective qualities. In section 5 a more detailed investigation is made of the behaviour of SI in different situations.

4.2. SUBJECTIVE EFFECTS PRODUCED BY A SINGLE CEILING REFLECTION

For completeness, mention should be made here of the qualitative observations made on the subjective effects of a ceiling reflection at $\alpha = 0°$ and $\beta = 40°$. The effects observed with a single ceiling reflection were: level change (similar to that produced by a side reflection), image shift and tone colouration. Both the latter were more intense than the same effects with a side reflection and occurred for the majority of delay and level situations. Somerville *et al.* [14] noticed this image shift with ceiling reflections; one localizes in between the direct sound and the ceiling reflection. Both Somerville and Schubert [6] note the tone colouration produced by ceiling reflections (or in Schubert's case non-lateral reflections). Somerville and others have observed that this colouration is also noticeable in halls with reflectors above the orchestra. More evidence, both from experiment and observation in real halls, is however required to substantiate this claim.

Ceiling reflections did not produce a spatial impression similar to that of side reflections.

5. THE VARIATION OF DEGREE OF SI WITH DIFFERENT REFLECTION PARAMETERS

Throughout this section a comparison technique was employed in the experiments. Subjects were presented with two reflection situations to compare; they could switch from one situation to another at any time, including *during* the passage of the music motif. In one reflection situation, consisting of the direct sound and a single reflection, the reflection level relative to the direct sound could be altered by the subject himself using the differential attenuator (previously mentioned in section 2.2). The other reflection situation, which at times contained more than one reflection, could not be altered. In each experiment, subjects were asked to adjust the differential attenuator until the degree of source broadening or SI appeared as nearly as possible the same in the two situations. They were told to ignore as far as possible any other subjective differences that they noticed. The Mozart motif was used throughout at a mean level of $E = 77$ dB (except in section 5.3).

The degree of SI for changes in reflection delay, direction and level will first be discussed for the case of a single side reflection, reverberation being added in one of the experiments. Finally experiments with two side reflections, and a ceiling and a side reflection will be described.

5.1. CHANGES OF SI WITH SINGLE SIDE REFLECTION

5.1.1. *Change of SI with reflection delay*

The spatial impression produced by a 40 msec delay side reflection (at $\alpha = 40°$) was compared with that of a side reflection with delay x msec coming from the same loudspeaker. Two experiments were conducted: one with the level of the x msec delay reflection variable and the other with the level of the 40 msec reflection variable.

By equating the degree of SI of the variable level x msec-delay reflection with that of the 40 msec-delay reflection at -6 dB relative to the direct sound, we derive a curve of equal spatial impression. This curve in Figure 5 was derived by 4–5 subjects (3 for the 80 msec case, and only 2 for 100 msec). It is evident from this curve, that for delays > 10 msec, only small changes of reflection level are required to maintain the same degree of spatial impression. The gradient of the curve for reflections arriving after 50 msec is 0·07 dB/msec. This can be compared with a gradient of 0·2 dB/msec for the aUs found by Reichardt and Schmidt [15], and gradients between 0·04 . . . 0·4 dB/msec for the threshold with different music motifs found by Schubert [6].

In the second experiment, the reflection delayed x msec was at -6 dB relative to the direct sound, while the 40 msec reflection had a variable level. It has been mentioned previously

(section 4.1.5) that the degree of SI increases with the level of a 40 msec side reflection. So the level, at which this 40 msec reflection gives the same spatial impression as the x msec reflection, is a measure of the degree of SI produced by the x msec delay reflection (at −6 dB relative to the direct sound). The results of this experiment, derived by the same number of subjects as are mentioned above, are given in Figure 7. The 95% confidence limits for the means are also plotted, these as surprisingly small considering the limited number of subjects used.
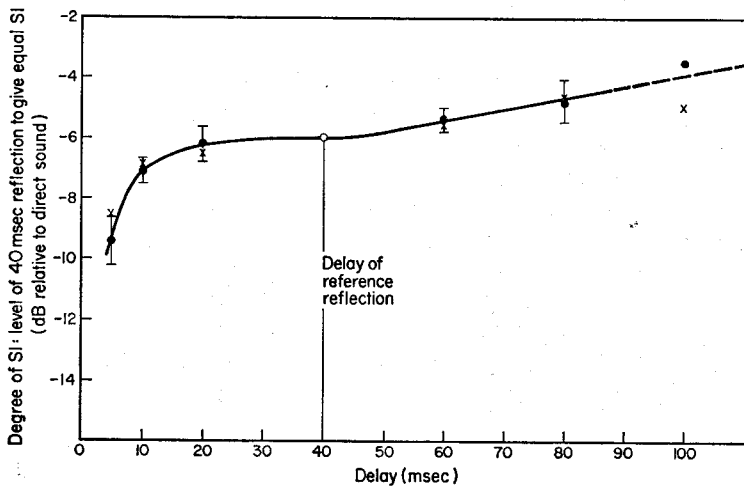

Figure 7. Curve of degree of SI against reflection delay for a single side reflection ($\alpha = 40°$). ϕ, Mean and 95% confidence limit of mean, no reverberation; ×, mean of results with reverberation.

Subjects found these experiments relatively easy, and spent less time comparing two SI's than when making a threshold measurement. Difficulty was experienced however for the extreme delay situations, where the two impressions for comparison were very different. For short delays (≈ 5 msec), there was a shift of the point of localization rather than a broadening of the source; while for long delays the subject had to try to ignore the disturbing qualities of the reflection.

The results in Figure 7 show that the degree of SI is predominantly independent of delay for reflections with delay between 10 and 80 msec. The second experiment was repeated with reverberation (at stationary level −8 dB relative to E and reverberation time = 1·5 sec) and a further reflection (−13 dB, 83 msec, −40°, −16°) added to produce a more natural sound. Subjects found this experiment more difficult, as was reflected in the 95% confidence limits, which were about double those without reverberation added. There was no significant change in the results by the addition of reverberation, the average points obtained are included in Figure 7.

5.1.2. Change of SI with direction of a lateral reflection

A limited number of experiments using three subjects were conducted comparing the degree of SI produced by a 40 msec-delay reflection coming from different lateral directions. Under these conditions the general relationships appeared as follows: that the highest degree of SI was produced for reflections with an azimuth around 40°, and that the degree of SI decreased slightly for larger angles of azimuth up to 90° and decreased down to zero for smaller angles.

Various factors made this experiment more difficult than anticipated. This was the only experiment where subjects had to compare sound coming from two not identically matched loudspeakers; there were also significant tone colouration changes which had to be ignored.

To get more accurate information, a more sophisticated technique is required which minimizes other subjective changes.

Using two "spatially" incoherent signals, one from directly ahead and the other at a variable angle of azimuth, Damaske [16] found that subjects were most sensitive at threshold level to sound with an azimuth of $\alpha = 100°$. Whether we expect his situation and the situation with a single coherent reflection to give analogous results is, however, an open question.

5.1.3. *Change of SI with reflection level*

The comparison technique does not lend itself to producing an absolute scale of degree of SI. We can however derive a relation of degree of SI for changes in the reflection level using the results of Reichardt and Schmidt [15], who measured the difference limen of a single side reflection ($\alpha = 60°$) of delay 35 msec. Reference to Figures 5 and 7 (in this paper) shows that the main effect of a 35 msec-delay reflection will be spatial impression, so it is reasonable to assume that the difference limen were determined from changes in spatial impression. A change in level equivalent to the difference limen can be considered as a change of one
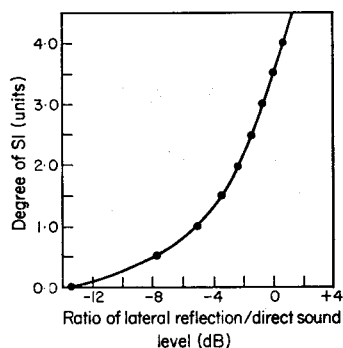

Figure 8. Curve of degree of SI against reflection level for a single side reflection for $\alpha = 60°$ (after Reichardt).

subjective unit of SI. Reichardt and Schmidt [17] describe a graphical method whereby we can derive a curve of SI against reflection/direct level from difference limen results. Using this method on the "Pegelerniedrigung" curve in Figure 3 of [15] starting at 0 dB reflection/direct sound level, we can obtain four of the points on the degree of SI curve that is given in Figure 8 (the points for degrees of SI: $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$ and $3\frac{1}{2}$).

The choice of 0 dB is however arbitrary as a starting point. Since from [15] for high level reflections the difference limen is constant at 1·5 dB, an interval of 0·75 dB is equivalent to half a subjective unit of SI at these high reflection levels. So we can obtain a new series of points in Figure 8 using the same graphical method but starting at +0·75 dB reflection/direct sound level. The interval between points in Figure 8 is thus half a subjective unit of SI.

The result in Figure 8 is much as expected from subjective observation; the curve is monotonically increasing and the rate of change of SI at low levels is much less than it is at high reflection levels.

5.1.4. *Conclusions about spatial impression produced by a single side reflection*

We see then that SI occurs for reflections of delay between 10 and 80 msec; its degree is principally determined by the reflection level relative to the direct sound, according to the curve in Figure 8. Adding reverberation did not affect the degree of SI. Mention should also be made of the result of de V. Keet [18], who found that the degree of SI (as measured by an apparent source width) depends on the level of the music; for soft music only very little spatial impression occurs.

It seems unlikely that the results derived in this section would be different for other music motifs, though threshold results of Schubert [6] for different motifs suggest that the results, such as in Figure 7, might be slightly at variance for very short delays. The effect of filtering the sound was not investigated, however in spite of large variations in instrumental content in the Mozart motif, *no* changes in SI occurred which would suggest that our results would be much affected by moderate filtering (like, for instance, that which occurs for direct and reflected sound passing at grazing incidence over an audience).

5.2. EFFECT OF TWO SIDE REFLECTIONS

Using the comparison technique again, subjects were asked to compare the degree of SI produced by two side reflections, with azimuth $\alpha = 40°$ and $\alpha = 60°$, with that of a single side reflection (z dB, 40 msec, 40°, −16°). Reflection delays of 40 and 29 msec for the two side reflections were used respectively; two pairs of reflection levels were used for two experiments: −9 and −9 dB, and −8 and −10 dB relative to the direct sound. These levels were chosen so that the incoherent sum of the levels of the two reflections was an exact number of dB's, i.e. −6 dB relative to the direct sound. Three subjects were used.

Out of the six results (2 experiments, 3 subjects), five of them gave the level of the single side reflection producing the same degree of SI as −6 dB, the sixth result was −7 dB, both relative to the direct sound. Subjects experienced little difficulty performing this experiment.

Thus, from this, admittedly limited, experiment it seems that for spatial impression the sound levels of side reflections add incoherently, that the degree of SI is determined by the ratio of lateral to direct sound.

5.3. EFFECT OF ONE SIDE AND ONE CEILING REFLECTION

The situation of a direct sound (−3 dB, 0 msec, 0°, −16°), a ceiling reflection (−5 dB, x msec, 0°, 40°) and a side reflection (−7 dB, y msec, 40°, −16°) was investigated for different delays, x and y. Subjects found that the subjective effects of the two reflections were additive, the side reflection produced SI while the ceiling one produced a vertical shift in localization and tone colouration. Three subjects, using the Vivaldi motif at a mean level of $E = 72$ dB, were asked to assess the degree of SI by comparing the two-reflection situation with a single side reflection situation (z dB, y msec, 40°, −16°). However the additional effects, produced when the ceiling reflection was added, made the two situations difficult to compare, and intersubject differences were larger than previously.

If the degree of SI is determined by the ratio of lateral to non-lateral sound (i.e. if for SI the ceiling reflection and direct sound levels add incoherently), then the level of the single side reflection to give the same degree of SI would be −6 dB relative to the direct sound. If adding the ceiling reflection has no effect on the degree of SI, the result would be −4 dB. The results that were obtained for the degree of SI varied between −2 and −6 dB for the level of the single side reflection relative to the direct sound. Results were fairly random, except that one pattern consistently emerged: that there is a slight reduction in SI (about 1 dB) for delays just more than compared with delays just less than that of the ceiling reflection. This "masking" effect by the ceiling reflection is consistent with the threshold results in section 3.3. The *change* in threshold of a side reflection (d_m in Figure 3) as its delay passes through that of the ceiling reflection is also a "masking" effect.

The smallness of this "masking" effect contradicts Marshall's suggestion [13] that the addition of a ceiling reflection (especially *before* a side reflection) greatly reduces the degree of SI. In fact, in no case out of 24 results did a subject in this experiment assess the degree of SI as less than −6 dB (side reflection level relative to direct sound), i.e. the degree of SI was not less than what it would have been if the ceiling reflection is considered as contributing (adding incoherently) to the direct sound.

This experiment suggested that the presence of a ceiling reflection and its delay have little destructive effect on the degree of SI.

6. DISCUSSION OF RESULTS AND OTHER AUTHORS' THEORIES

The principal determinant of the degree of SI appears from section 5.1 to be the reflection level; for delays of between 10 and 80 msec the actual delay has little effect on the degree of SI. With two side reflections, the degree of SI is given if the incoherent levels of the side reflections are added. Also a ceiling reflection has little destructive effect on the spatial impression.

From the evidence of these experiments an objective measure, viz. the ratio of lateral to non-lateral sound arriving within the first 80 msec, appears uniquely related to the subjective degree of spatial impression. How significant the choice of the delay limits is in the real case is not known, though preliminary theoretical studies of concert halls suggest that the choice is not critical—others have considered early sound to be that arriving within the first 50 msec. Lateral reflections of short delay ($<$ 5 msec), which would increase the ratio of lateral to non-lateral sound, produce little SI (see Figure 7); however in real halls such reflections are the exception rather than the rule. The ratio of lateral to non-lateral sound will be referred to as S dB.

Schroeder et al. [19] measured the ratio (S dB) of lateral to non-lateral sound arriving within the first 50 msec in the Philharmonic Hall, New York. They also suggest that changes in this ratio throughout the hall may be objective measures of subjectively noticeable differences.

It was found in section 4.1 that SI was the only positive subjective effect produced by early reflections. The ratio, S dB, therefore appears to be a measure of the positive subjective effect produced by early reflections. Other authors have used different quantities to measure the positive effects of early reflections. We shall now discuss how these other quantities are related to the ratio S dB.

6.1. IS A HALL'S CROSS-SECTION RATIO RELATED TO SPATIAL IMPRESSION?

On the basis of personal experience listening to music in halls, Marshall [13, 20] proposed that there is a desirable subjective quality present when music is played in classical rectangular halls, which is not present in fan-shaped, low-ceiling halls. He traced this quality, termed "spatial responsiveness", to the presence of unmasked lateral reflections in classical halls, reflections which he claims will be masked in the case of low-ceilinged halls. In his first article he then proceeded to propose a criterion for good halls based on the cross-section ratio (the ratio of hall width to height), good halls having a small cross-section ratio.

Marshall's thesis is based on the need for unmasked lateral reflections. However certain reflection situations, for which lateral reflections are considered masked by Marshall, may have a satisfactory level of SI (measured by S dB). Marshall's analysis in Figure 2 in [20] deals with the situation at the frequency (about 150 Hz) of maximum audience absorption due to grazing incidence. If we consider the whole frequency range the predominance of the ceiling reflection is reduced; on the basis of the results of section 5.3, lateral reflections arriving after the ceiling reflection can make a useful contribution to SI. Furthermore by considering all reflections within 80 msec of the direct sound the ratio (S dB) of lateral to non-lateral sound reflects better the subjective impression. The relationship between hall cross-section and the degree of SI cannot be simply predicted and further subjective information is required, derived from experiments similar to those reported here, to determine the significance of audience absorption in real reflection sequences.

The cross-section ratio is certainly in some cases related to the ratio of lateral to non-lateral sound. A narrow hall (small cross-section ratio) will produce strong lateral reflections, and thus have a high ratio, S dB. It seems unlikely, however, that the cross-section ratio would correlate *in general* with the ratio, S dB. Take the case of halls with the same cross-section ratio, using a constant source-receiver distance: if the height and width are increased, the level of the side reflections will decrease relative to the direct sound and the ratio of lateral to non-lateral sound will also fall (in spite of a fall in the level of the ceiling reflection). Thus cross-section ratio does not seem uniquely related to the degree of SI. West [21] has, however, obtained a good correlation between cross-section ratio and overall acoustic quality in halls. Further investigation is definitely required to resolve how useful cross-section ratio is as a determinant of acoustic quality in a concert hall.

6.2. IS SPATIAL IMPRESSION AN AUDITORY CROSS-CORRELATION PROCESS?

Keet [18] using stereo recordings of single source reproductions of orchestral music in real halls replayed them to subjects who were then asked to measure the degree of spatial impression by assessing the apparent source width in degrees. He suggested that in arriving at an apparent source width the ear performs a short-term cross-correlation between the signals arriving at each ear, a process similar to that employed in localization. An objective measure was established by recording the impulse response of the hall in a pair of stereo microphones; the short-term cross-correlation coefficient is then the measure of coherence between these two impulse responses. If A and B are the normalized impulse responses in the two microphones, so that

$$\int_0^{50\,\text{msec}} A^2 \cdot \mathrm{d}t = 1 = \int_0^{50\,\text{msec}} B^2 \cdot \mathrm{d}t,$$

then the cross-correlation coefficient is

$$K_0^{50} = \int_0^{50\,\text{msec}} A \times B \cdot \mathrm{d}t.$$

He found that there was a straight line relationship between the subjective apparent source width and the objective degree of incoherence $(1 - K_0^{50})$, as measured with stereo microphones. A high degree of incoherence corresponded to a large apparent source width. A similar result was also obtained by Damaske [16] using a synthetic sound field: that the solid angle from which sound is perceived increases as the coherence between loudspeaker signals decreases.

If we make certain assumptions, we can obtain a relation between the coherence at one's ears K_0^{50} and the ratio of lateral to non-lateral early sound, S dB. We assume:

(1) that the early sound is divided into non-lateral, left and right;
(2) that the left-hand ear is insensitive to sound from the right, and vice versa (i.e. infinite effective head shadow);
(3) that each ear is equally sensitive to non-lateral sound as it is to sound from its own side.

The assumptions will be discussed below.

If S_1 is the ratio of left early sound to non-lateral early sound in dB, and S_r is the corresponding ratio for the right, then it can be shown that

$$K_0^{50} = \left[\left(1 + \text{antilog}\frac{S_1}{10}\right)\left(1 + \text{antilog}\frac{S_r}{10}\right) \right]^{-1/2}. \tag{1}$$

If we are near the centre of a symmetrical hall, we can assume

$$S_1 = S_r = S - 3 \text{ dB}.$$

So

$$1 - K_0^{50} = \text{antilog}\left(\frac{S-3}{10}\right)\Big/\left[1 + \text{antilog}\left(\frac{S-3}{10}\right)\right]. \tag{2}$$

This quantity $(1 - K_0^{50})$ is in fact simply the ratio of the intensity of the right-hand sound to the sum of the intensities of the non-lateral and right-hand sound. (Left-hand is interchangeable for right-hand here, since $S_1 = S_r$ has been assumed.) Let us see how valid equation (2) is.

Assumption (3) above is arbitrary, as changes in the sensitivity correspond simply to a small shift in the S-scale. Assumption (2) is definitely not true in reality. Let us say that, with sound coming from the left, the ratio of the pressures in the right and left ears is r $(r < 1)$, and vice versa. Then, since sound from one side does not arrive simultaneously in both ears, the fact that both ears receive the sound simply causes the incoherence to increase. The
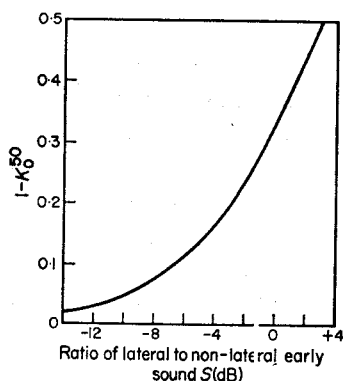

Figure 9. Relation between degree of incoherence $(1 - K_0^{50})$ and ratio of lateral to non-lateral early sound S (dB).

intensity of all right-hand (or left-hand) sound increases by a factor $(1 + r^2)$, and equation (2) is again valid if we shift the S-scale a certain number of dB. To take an example: an average figure for the relative sensitivity of each ear to sound coming from the opposite side is 6 dB, then $r = \frac{1}{2}$ and the S-scale will have to be shifted 1 dB. Thus we see that assumption (2) is not necessary, by dropping it there will only be a small shift in the S-scale.

Equation (2) is therefore valid for $(1 - K_0^{50})$ measured at one's ears. Keet, for his determination of the incoherence, used microphones with a directional sensitivity approximating to that of the human ear, at least for sound from in front (sound arriving on axis in one microphone was attenuated by about 5 dB in the other microphone at middle frequencies [22]). The relation in equation (2) is plotted in Figure 9.

In section 5.1.3 we derived a scale of SI for changes in reflection level, Figure 8. The abscissa in this figure is in fact the ratio S dB (though the ceiling reflection present in Reichardt's experiment may mean that the abscissa values in Figure 8 are slightly larger than S dB) Figures 8 and 9 appear very similar; to determine how the degree of SI is related to $(1 - K_0^{50})$, using S as a common parameter, the two quantities are plotted in Figure 10. (The author is most grateful to Mr W. de V. Keet for suggesting the inclusion of this graph.) The relation is surprisingly linear except at the lowest values of S, where in any case Reichardt's curves have a high margin of inaccuracy. The divergence from linearity is in fact reduced if $(S - 4)$ is used in equation (2) rather than $(S - 3)$. Various possible small shifts in the S-scale have been mentioned above; one or more may be responsible for this.

So we can conclude that $(1 - K_0^{50})$ measured at one's ears or measured with a pair of stereo microphones is a linear measure of the degree of SI as is the subjective apparent source width measured by Keet [18].

At the end of his paper, Keet mentions a case of degeneracy, when one hears two equal delay, equal level reflections from opposite sides the predicted degree of incoherence is zero. This produces a very interesting subjective experience. Subjects were presented with direct sound (−3 dB, 0 msec, 0°, −16°) and two side reflections (−6 dB, 40 msec, 40°, −16°) and (−6 dB, 40 msec, −40°, −16°), and were asked to compare their impression of this arrangement with that when the reflection delays were different. While, in general, varying the delay of reflections produces little change in the subjective impression, all subjects agreed that there was definitely something different about the degenerate case, and found the degree of spread
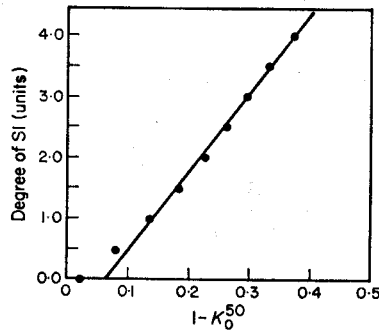

Figure 10. Relation between the degree of SI and the degree of incoherence $(1 - K_0^{50})$.

of the sound much less in this case. By moving one's head about 30 cm to each side, one returned to the normal impression with two side reflections. This last experience compares with the simple localization experiment when two loudspeakers, as in a stereo system, are fed with the same signal. Upon moving one's head adequately to introduce a time delay of 0·6 msec (path length difference 20 cm) between the signals at each ear, the point of localization moves from between the loudspeakers to the loudspeaker nearest one's head. The degenerate case, is however, unlikely to be of significance with an orchestra playing in a real hall with many reflections, but it lends further support to the cross-correlation theory.

There is considerable evidence in the literature to suggest that the ear's localization process is based on cross-correlation. One way of looking at the process involved in producing an apparent source width is to assume that for each reflection the ear performs a localization, or lateralization, process to establish the reflection's directions; an apparent source width is then constructed accordingly [23]. The net result can, of course, be described as a cross-correlation process on the whole sound field.

6.3. HOW IMPORTANT IS INITIAL-TIME-DELAY GAP?

Beranek, in his investigation of concert hall acoustics [24], proposes that the initial-time-delay gap (the delay of the first reflection relative to the direct sound) is the most significant determinant of acoustical quality in a concert hall (i.e. more significant than reverberation time). He relates the initial-time-delay gap to the subjective quality of "intimacy"; for a hall to have the right degree of intimacy it must *sound* as if it were the appropriate size for the music being played there. For optimum intimacy, he claims that the initial-time-delay gap must be less than 20 msec.

If Beranek's theory is correct, we would expect a reflection of delay less than 20 msec to produce a highly desirable sensation of apparent room size, which is not present with longer

delays. Our observations (e.g. Figure 5) have shown however that reflections of less than 20 msec delay produce *no* positive contribution to subjective impression *which is absent for later reflections*, certainly nothing so obvious as to make the difference between an excellent hall and only a good one. A short experiment was conducted in which subjects were asked to compare subjectively reflection sequences (including reverberation) with a short and a long initial-time-delay gap side-reflection (keeping the ratio S dB constant). They found that delay bears very little relation to the apparent room size, but that reflection level is much more significant. They did however observe that, while lateral reflections give some impression of acoustical spatial dimensions, altering the ratio of early to reverberant sound produced very large changes in the apparent room size. Beranek and Schultz [25] have found this ratio of early to reverberant sound very significant in real halls.

The relation between S dB and the initial-time-delay gap depends on whether the first reflection comes from a side wall or from the ceiling. If it comes from a side wall, as in narrow classical halls, a short initial-time-delay gap will correspond to a large value of S dB and hence a high degree of SI. If the first reflection comes from the ceiling no such correspondence occurs.

7. CONCLUSIONS

The subjective effects of a single side reflection have been investigated and "spatial impression" (SI) or broadening of the source was isolated as the only positive subjective effect other than loudness effects, the principal determinant of the degree of SI was found to be the side-reflection level (relative to the direct sound); delay is relatively unimportant for reflections delayed between 10 and 80 msec. Ceiling reflections however did not produce this effect, but only produced tone colouration. The effect of early side reflections is distinctly different from that of reverberation: experiments with early reflections gave the same results with and without a reverberant field present.

While we were limited to simple reflection situations, the degree of SI for more than a single side reflection appears to be related to the sum of the powers of the lateral reflections. It was proposed that the degree of SI can be measured by the ratio of lateral to non-lateral energy arriving within the first 80 msec, the same ratio as was used by Schroeder [19].

Further evidence was produced to support Keet's hypothesis [18] that the degree of spatial impression is related to the degree of incoherence between signals picked up on a stereo microphone system or at one's ears. We found that Keet's cross-correlation coefficient is monotonically related to the ratio of early lateral to non-lateral sound. By comparison with difference limen results of Reichardt [15], it was found that the degree of incoherence $(1 - K_0^{50})$ is a linear measure of the degree of spatial impression.

Marshall's theory [13] was reviewed, but his suggestion that a lateral reflection must arrive before a ceiling reflection for an SI to be created conflicts with evidence gained here. Without measurements in real or model halls it is not possible to say how much the degree of SI depends on the cross-section ratio of the hall. From experiments described here, there was no evidence to support Beranek's theory [24] that a short initial-time-delay gap is, *a priori*, a guarantee of an excellent concert hall.

Much more evidence is required in the form of subjective impressions in halls relating to spatial impression. Marshall claims that the subjective effect of early lateral reflections has previously been assigned to reverberation, which explains why spatial impression has been ignored until recently. To establish spatial impression as an essential quality of concert halls, measurements must be made of variations in the ratio of lateral to non-lateral early sound both in individual halls and between halls to see if this correlates with subjective evidence. Model tests can then establish suitable and unsuitable hall shapes.

The experiment also suggested that the ratio of early to reverberant sound and the tone colouration produced by ceiling reflections are two other important subjective qualities. Simulation experiments, objective and subjective evidence in real halls might also help to elucidate these qualities.

ACKNOWLEDGMENTS

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