

A NOTE ON THE IMPORTANCE OF ROOM CROSS-SECTION IN CONCERT HALLS

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Spatial responsiveness (SR) is identified as a desirable property of concert halls usually associated only with classical rectangular concert halls. Two halls, of classical and modern shape, are compared, and their echograms are subjected to a masking analysis based on the work of Seraphim. From masking consideration it is concluded that SR occurs in halls in which masking of one or more major reflections by others is a minimum because: (a) no two reflections of the same direction in the first 100 msec after the direct sound are temporally adjacent, (reflection here includes the direct sound); (b) the major reflections (skeletal reflections) are not bunched but tend toward even spacing after the direct sound.

Some architectural conclusions are drawn relating room cross-section to orchestral width, and these are compared with experience in existing halls.

1. INTRODUCTION

1.1. ARCHITECTS' VIEW

The variety of shapes found in concert halls built during the past few years, the claims advanced for them by their authors, and their general acceptability by the public, gives weight to the belief, at present widespread amongst architects, that virtually any room shape may be made "good" acoustically, given suitable treatment to control reverberation and diffuseness. Acousticians' claims to have "corrected" domes (1), curved walls (2), huge seating areas (3) and the like contribute nothing except a formal *carte blanche* as an acoustical design determinant for architects. Specification of the requisite absorptive or diffusing treatment is usually a major part of the consultancy which follows, and the result is often "good".

Recently, the necessity to compare predicted acoustical properties for five concert hall designs brought home to the author the paucity of reliable design criteria relating to room shape (as distinct from room details such as balconies, floor rake and so on). The following ideas are presented in the belief that, though based on extrapolations and assumptions from experiments by others, they make a *prima facie* case for a formal design determinant (formal here is used in the architectural sense relating to the form of the room), in terms of the quality of sound desired or expected in the proposed room.

1.2. THE DESIRED QUALITY

In spite of the initial statement that most halls designed as described above turn out to be "good", some halls, often regarded as the best, have a quality of sound which is missing in the others. This quality has been variously attributed to the reverberant conditions, and to the arrival time of the first reflected sound. It is suggested in this note that the reverberation conditions evidently have only marginal relevance to it (both preferred and other halls may well have the same reverberation time) (4) and that the

masking of major reflections by others due to their mutual arrival order is more significant than the initial time delay (5).

1.2.1. *Identification of the quality*

To aid in the identification of the quality sought, it is observed that: (a), as a property of the *sound*, it is related to the loudness attributes; (b), as a property of the *hall*, it carries the idea of spatial responsiveness to the music; (c), for the *listener*, it generates a sense of envelopment in the sound and of direct involvement with it (5) in much the same way that an observer is aware of his involvement with a room he is in.

As far as the author is aware, no satisfactory name at present in use conveys these ideas (many of which have in the author's opinion been hitherto wrongly attributed to the reverberation conditions), and for want of a better name "spatial responsiveness" (SR) will be adopted in the remainder of this discussion. Many halls without SR are considered good, though attempts to increase the reverberant sound in such halls suggest awareness of a certain lack, even in such good halls. If, as is suggested here, SR is primarily a property of the room shape, such attempts can be seen to be of marginal significance.

Classical rectangular halls typified by those at Boston and Vienna usually have this quality. Fan shaped, low-ceilinged halls usually do not.

1.3. REVERBERATION

It is not intended to establish more thoroughly the assertions relating to SR quality made in the foregoing section, as the note is tentative and exploratory. The author believes that consideration of critics' views on various halls, in the hope of establishing a consensus of opinion, can too easily delude one that a personal view has been proven in general. The views expressed here are based on the author's personal experience of listening systematically to music in halls. It has been observed that during the course of a piece of music the reverberant sound is barely perceptible even in a live hall, until a rest or pause allows one to hear it. It seems rather that a reverberant room produces a *set* of the auditory process which enables one to listen selectively to the significant acoustical events as they take place, a set which makes an acoustical contribution to one's awareness of the room. Reverberation provides an acoustical context within which the significant acoustical events are perceived. It also seems probable that this context will vary from person to person, depending on such factors as attitude to the music, familiarity with it, and attention. In particular the musician making the music depends upon room reverberation as an essential acoustical feedback. (See section 7.1 for an explanation of why this should be so.) There is no doubt that reverberation is essential to musicians.

These views on the nature of perceived "reverberation" arise in part from the observation that halls of comparable size which have the same measured reverberation time but different shapes, have very different "reverberation" effects (e.g. warmth, liveness, fullness, etc.). It is as if one cannot hear the *effects* of reverberation during music in some halls, even though one can measure the presence of reverberant sound (6). The implication is that these *effects* are not produced by reverberation at all.

1.4. THE QUESTIONS

The quality of musical sounds heard in a concert hall is known to depend upon (a) details of early reflection sequences; (b) the integrating and masking performance of binaural hearing relative to these sequences; (c) reverberation.

The questions which arise are as follows.

1.4.1. Why is SR apparently lacking in broad or fan-shaped halls, while it usually does occur in rectangular narrow, high halls?

- 1.4.2. Can SR-lack be related to qualities hitherto ascribed to lack of reverberation ?
- 1.4.3. Is there a notable difference in the details of early reflections sequences in the two types of concert halls here considered ?
- 1.4.4. Is available experimental evidence—notably provided from research at Göttingen—useful in elucidating the significance of such differences ?
- 1.4.5. Can such data produce architectural design criteria relating to SR ?

2. PROCEDURE IN GENERAL

The procedure followed in investigating the main questions 1.4.1 and 1.4.3 started in considering two simplified halls: one was based upon the Boston Symphony Hall (7), cross-section 75 ft wide \times 63 ft high, the other being also rectangular, but having cross-section 120 ft wide \times 50 ft high. No suspended reflectors, galleries, tapered walls or sloped ceilings are assumed, and the floor is considered to be flat. It will be seen that this is an unlikely format for a hall and it is proposed to deal later with the effects of modifications to this shape which will bring it more into line with existing halls.

It will be noted that the hall cross-section is specifically stated. For some reason it is unusual to find hall cross-sections illustrated in acoustical texts, most rooms being represented in plan and long sections. Yet it is in cross-section that some of the major variations occur.

It was found necessary to identify the principal lateral and overhead image positions (8). An orchestral width of 45 ft was assumed. (The effect of different orchestral widths is discussed in section 9.) Path time differences from the two extremities and the centre of the orchestra were then calculated to a seat 60 ft from the stage in the centre of the hall. Relative levels for the reflections were assumed. Data from Seraphim (9), modified as below, were then used to draw the absolute threshold of perceptibility for reflections, and conclusions were drawn about the room shape in relation to this threshold.

3. NOTATION

To represent the sense in which a particular image occurs, the orchestra is shown as a tapered block on the drawings. The relative height of the ends has no quantitative significance. A_0, B_0, P_0 are the two extremities and the centre of the orchestra, respectively. Image 1 (A_1, P_1, B_1) is the ceiling image. Images 2 and -2 (B_2, P_2, A_2 and $-A_2, -P_2, -B_2$) are the right and left side wall images and images 3 and -3 with corresponding letters, are the second-order ceiling-and-wall, or cornice, images, respectively. The direct sound and the reflected sounds are identified on the constructed echogram by the number and letters of their images of origin.

Figure 1 shows these sources and images in elevation on the cross-sections. Represented are the main reflections which arrive at the seat chosen within the first 100 msec or so after the direct sound. Surfaces near the stage itself have been left out as so much variation between halls occurs in this region that the reflections originating there must be treated as special cases in the echogram (see later section 7.1).

4. REFLECTION SEQUENCES

Figure 2 shows the resultant echograms for the two halls, the tall lines representing the "tall" side of the orchestra and so on. The side wall reflections have been left unshaded to avoid confusion, where they overlap the other reflections.

One sees immediately the characteristic *bunching* of reflections in the wide hall, and *even* spacing in the tall hall Y (10). A possible source of the "enveloping" attribute of SR is also apparent in the time compression of the three overhead images for the Y hall. In

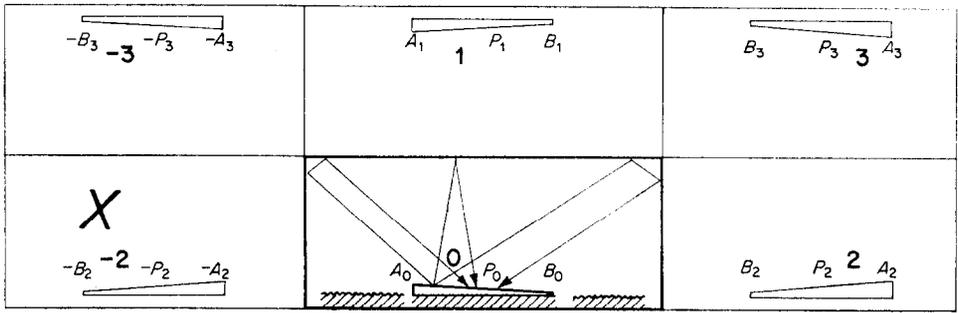


Figure 1. Cross-sections of halls with images.

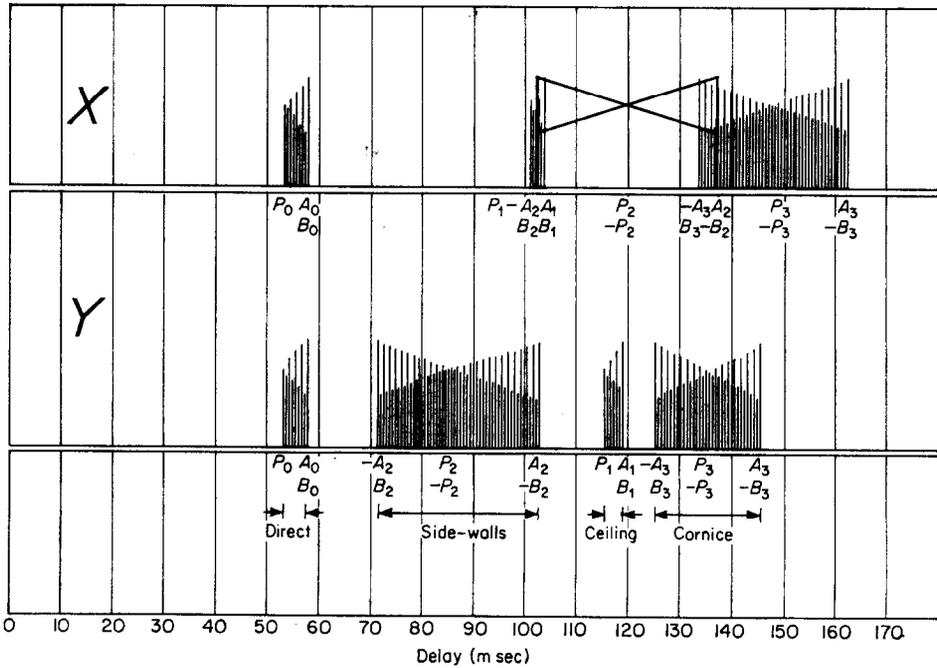


Figure 2. Orchestral echograms for the two halls.

only 30 msec the strong overhead reflections re-present the orchestra threefold with an angle subtended at the listener's seat of four times that of the original source. On the other hand, in the X hall the same reflections are spread over double the time interval (60 msec). One effect of such a time compression in the reflected sound would be enhanced integration of these reflections by the listener and consequent enhancement of the loudness attributes of the sound.

5. SUMMARY OF PREVIOUS RELEVANT WORK

One of the aims of Seraphim's work was expressed: "In addition it is hoped to explore the possibilities of transforming a measured or constructed echogram into an acoustical impression by reproducing the individual reflections electro-acoustically in an anechoic room—in this way one might expect to obtain a natural room impression. Meyer and Schodder... found that one cannot forego reverberation in the representation." ("Zugleich sollen die Möglichkeiten geprüft werden, ein gemessenes oder errechnetes Echogram

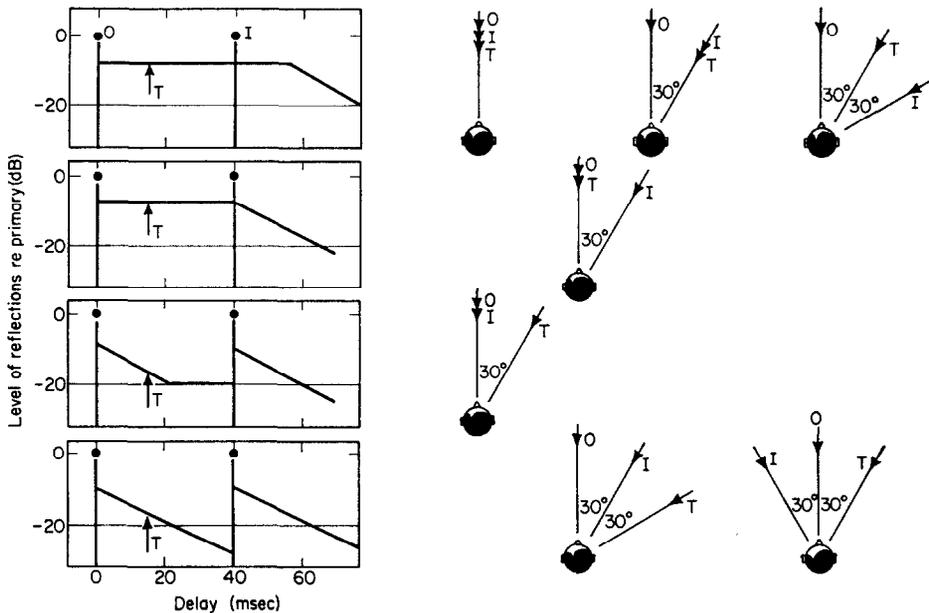


Figure 3. Summary of Seraphim's work—variations in threshold for various directions: *o*, primary; *I*, masking; *T*, masked sounds.

dadurch wieder in einem akustischen Eindruck zu verwandeln, dass man in einem reflexionsfreien Raum die einzelnen Rückwürfe electroakustisch nachbildet... und man einen natürlichen Raumeindruck erwarten sollte, ... Meyer und Schodder... fanden dass man auf die Nachbildung des Nachalls nicht versichten kann.") (11). The threshold he used as a criterion for this work he defined as the "absolute threshold of perceptibility", "that threshold above which a reflection contributes either by an impression of loudness or by any other impression" and further pointed out that for a contribution to sound quality or directional impression we require a slight modification of this threshold. The modified threshold, he suggests, lies slightly above the former as determined by the "constant stimuli method" but from his results, very close to the value determined by the "judgements method". There seems to be no reason why the same approach should not be applied to the design of rooms. He also showed that the shape of the masking curve does depend upon the relative directions of the reflections involved.

In the course of his work he determined that relatively few of the very numerous reflections need to be included in an electro-acoustical representation of an echo sequence in order to simulate the room impression, because of the masking of the majority of echoes in an echogram by the few strong components. For the first 100 msec or so the reverberation is completely hidden by these masking effects, and thereafter it in turn determines the masking. Finally, the effect of any one reflection is determined mutually by the entire sequence.

Seraphim used continuous speech, appropriately delayed, for his sound sources, so that the instantaneous spectral content of direct and delayed signal was not the same, and determined this absolute threshold for a limited number of directions, for both single and multiple reflections, and with variations in both level and delay. Figure 3 summarizes the directional effects he found.

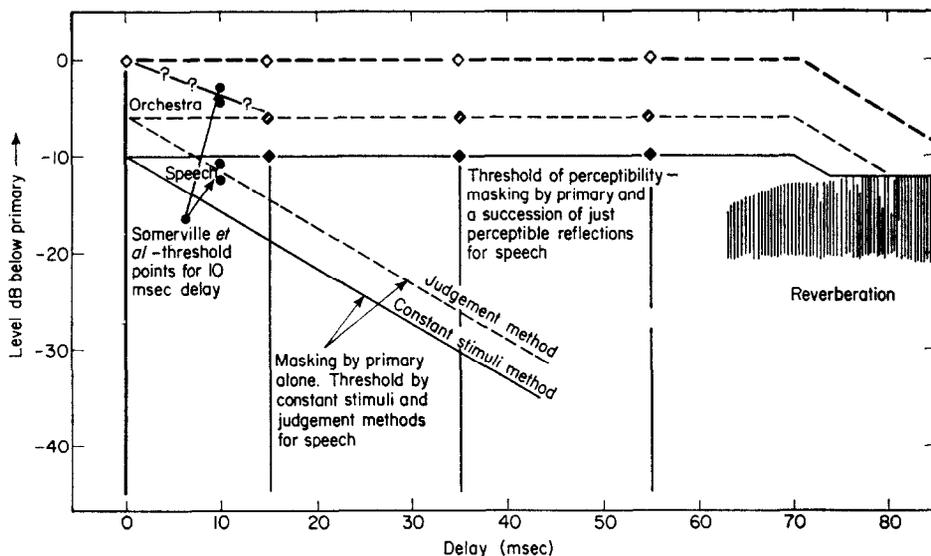


Figure 4. Summary of masking data for sounds of the same directions: (—◇—◇—) suggested threshold for orchestral music masking by primary and reflections; (—◆—◆—) judgments method for speech; (—◆—◆—) constant stimuli method for speech.

More recently Somerville, Gilford, Spring and Negus (12), using a method comparable with the "judgements method", determined the same threshold for a variety of sounds, including orchestral music. Their results for speech are in good agreement with comparable results from Seraphim but they considered only a single delay time of 10 msec. Nevertheless this one measurement indicates that the masking effect of music upon a single succeeding echo is far greater than for speech. Since both music and speech are continuous acoustical events, one may suppose that the general masking effects found by Seraphim for speech would have closely related, but generally greater, counterparts with orchestral music.

On this basis the suggested masking is shown in Figure 4. It is suspected that the slope of the masking curve for music would be more toward horizontal (in the direction of prolonged masking) but conservatively the same slope as for speech has been adopted, raised overall by the amount suggested by the one point we have from Somerville.

This approximate information cannot, of course, do more than indicate a tendency, and suggest further research, particularly regarding the detailed effects of direction, and of possible spectral changes in the reflected sound, upon masking of orchestral music.

6. FURTHER DATA REQUIRED

Before Seraphim's modified data can be applied to our constructed echograms two further pieces of information are required.

Will there be significant differences in the relative level of the reflections, and can a procedure be found to rank the reflections in some sort of masking order?

It is certain that because of audience absorption of direct sound and wall reflections at grazing incidence in the X (wide) hall, the main overhead reflection will predominate in the echo sequence for this room. On the other hand because of the narrowness of the other hall any significant difference in the strengths of the reflections is not likely. One therefore assumes the changes in level for the reflections relative to the direct sound as shown in Table 1.

TABLE 1

	Direct (0)	Ceiling (1)	Sidewalls (2, -2)	Cornice (3, -3)	
X hall	0	0	-5	-2.5	dB
Y hall	0	-2.5	-2.5	-2.5	dB

The procedure is not straightforward, because if a reflection crosses the threshold it immediately changes the shape of the threshold due to its own masking effects. It is suggested that sound reaching an observer may be considered as consisting of the main reflections which determine the overall shape of the threshold (skeletal reflections), and scattered sound which is perceived in the context of this overall shape. It is clearly possible, from Seraphim's work, for one or more of the main reflections to be masked completely by the others depending upon their relative levels, directions and delays. In the short time interval considered here, it is also reasonable to assume that the scattered sounds from irregularities in the room boundaries will have the same direction as, and similar delays to, the skeletal reflections they accompany.

One first considers the skeletal reflections, therefore, to determine any mutual masking and then draws in a second threshold with respect to the scattered sound at any time. Finally, direction is considered in azimuth, in the 0 and 1, 2 and 3, and -2 and -3 reflections, each pair of sounds having only one direction relative to the observer's head.

7. DISCUSSION OF MASKING SHOWN

The echogram shown originally in Figure 2 for hall X has, by chance, the (1) reflection intersecting the (2, -2) reflections, so that for some instruments the reflection arrival order is different at the seat considered from the arrival order for others. For clarity in the masking diagrams, shown in Figure 5, this reflection has been shifted forward slightly (as indeed it often is by a reflector hanging over the orchestra).

7.1. SKELETAL MASKING

The most significant result here is that the side wall reflections in the X hall are completely hidden in the echo sequence by the masking from the strong early overhead reflection and the relatively strong cornice reflections. This obtains *for all instruments*

and is brought about by the bunching mentioned before and the repeated direction of adjacent reflections. For the *Y* hall, however, all the skeletal reflections shown are significant.

It is clearly advantageous to have the main ceiling reflection preceded by lateral reflections.

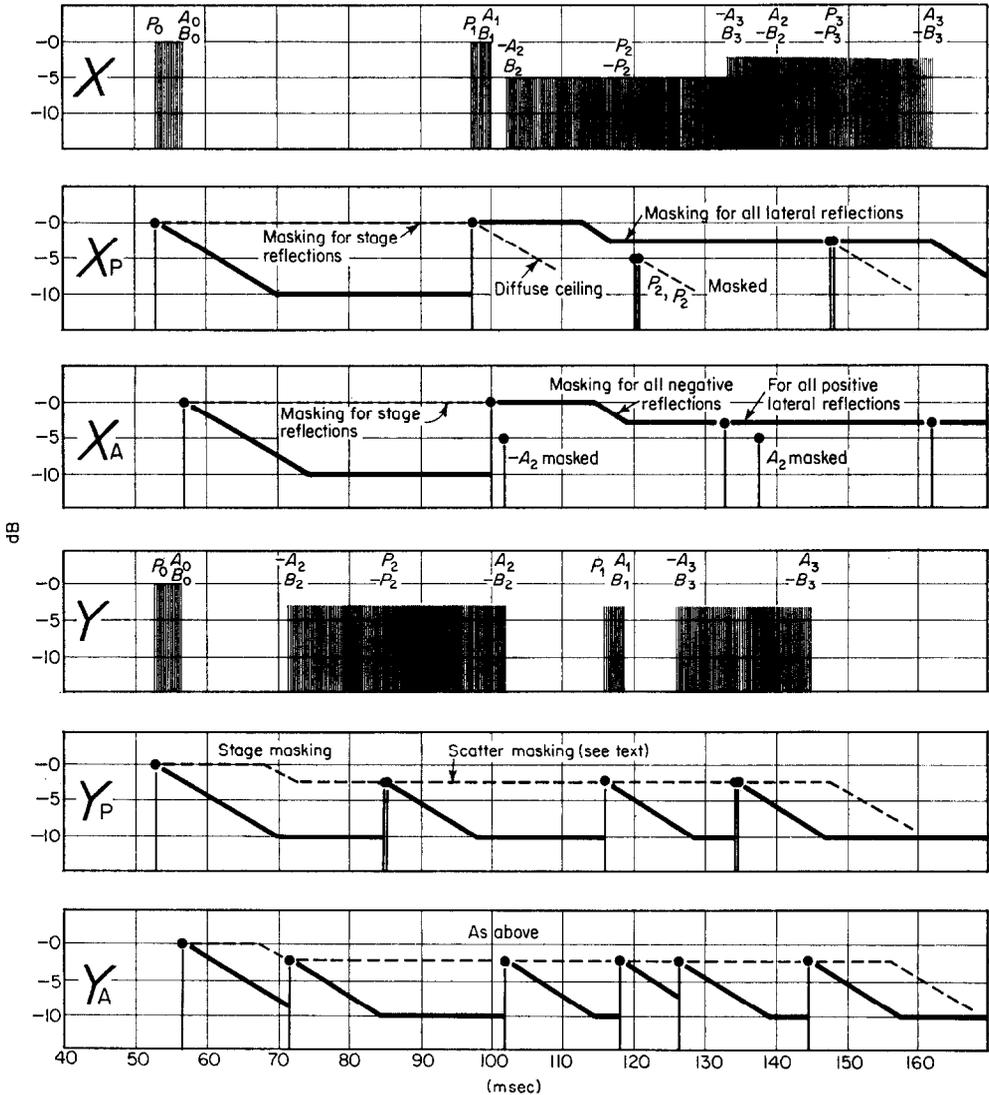


Figure 5. Skeletal and scatter masking for the echograms: *P*, centre of orchestra; *A*, one extremity.

A second interesting result concerns the region between the direct sound and the first reflection, in both halls. Since the only sound which is likely to arrive during this interval comes from the stage—i.e., has the same direction as the direct sound—the masking is relatively high for both halls. In other words, only reflections comparable in loudness with the direct sound will be heard from this direction at this time. The presence of these further skeletal reflections, if any, can be seen from Seraphim's results to cause no variation to the overall masking. On the other hand, stage area scatter will be completely masked, and stage enclosures should thus be designed for the benefit of the performers in this

regard, and not for that of the audience. However, one should note that in the instrumental area a high masking level is likely due to the relatively high levels of the instrumental sounds. This would account for musicians' dependence upon reverberation, as the early reflections which create the nuances of SR for the audience would be masked for the musicians. Stage enclosures should thus be designed to promote local reverberation for the performer's benefit.

Added weight is thus given to the comments made in (4) above. In the *Y* hall, with SR, the effective main reflections do surround the observer's auditory "view" in a manner which is wholly consistent with the idea of envelopment as an SR factor, but in the *X* hall, without SR, one is limited to the overhead reflections which are themselves so widely separated as to make integration less likely. Noticeable lateral echoes are known to be a problem in wide halls and it is very commonly found that absorbents are installed in the region of the cornice on either wall or ceiling or both, to suppress the "3" reflections. This then leaves only the overhead reflection effective of the five discussed in this note for such halls. A predictable major difference in the sound in the two halls under these circumstances is thus clear.

7.2. SCATTER MASKING

Scatter masking will vary with the course of the reflection sequence, being produced sometimes in one direction and sometimes in another, depending upon the relative directions of preceding, following, and scattered sound. It is probably also significant that at the end of the sequence the reverberant sound (assumed to be 10 dB below the direct sound in both halls) will be heard some 30 msec earlier for the *Y* hall than for the *X* hall, when the masking threshold crosses the peak reverberant levels.

7.3. THE EFFECT OF SITTING NEARER A WALL

Variations in the orchestral echogram produced by considering a seat near a side wall are not important in the case of hall *Y*. Hall *X*, on the other hand, has several important changes for the better since the wall reflections from one side at least would then clearly precede the overhead reflection. This is borne out in experience. The sound near a side wall in a wide hall is better than that in the centre, but, as one would expect, orchestral balance is not always good. Clearly, if for some instruments masking occurs and for others it does not, due to the relative arrival times described above, imbalance in the sound must follow.

7.4. GENERAL CONCLUSIONS

The inter-reflection masking in an echo sequence is determined by the directions of the reflections concerned, their level, and their time spacing. Since in the worst case—the masking following a pair of reflections from the same direction—the sustained level is maintained (for speech at least) for only 15 msec after the masking reflection, extremely wide rooms could give rise to sufficient separation between the overhead reflection and the wall reflections to make the wall reflections perceptible. In such cases a low orchestral canopy would not detract from the sound in any way. Rather, positive improvement in loudness is likely. This, the author believes, is the case at the Tanglewood Music Shed, where inter-reflection times of about the right magnitude were shown to exist in reference 1, p. 449. Thus a low canopy cannot always be said to cause undesirable effects, though for more common room sizes it usually does.

8. ARCHITECTURAL CONSEQUENCES

8.1. GENERAL

The accuracy of the above work is obviously determined by the lack of precise information on orchestral masking and the directional limitations of Seraphim's work. A few general conclusions may however be drawn.

8.2. EFFECT OF DIFFUSING AREAS IN THE CEILING

Acoustical texts often exaggerate the amount of diffusing surface present in the main room surfaces in the classical halls. A notable example is the Grosser Musikvereinsaal at Vienna where the ceiling is, in fact, almost flat. Diffuseness, according to the above argument, would not be particularly significant in such a hall. On the other hand diffuseness in the ceiling of an *X* type room is advantageous in two ways. In the first place, it degrades the strength of the main ceiling reflection and thus lowers the masking level, perhaps sufficiently to allow the wall reflections to count. Second, it may provide lateral directionality to the overhead reflections which will decrease the stage area masking and generally improve the masking situation.

8.3. EFFECT OF CROSS-SECTION RATIO

Even with the simplifications adopted here, it is evident that the shape of the cross-section is of fundamental importance in determining the arrival order of the reflections discussed. The fundamental difference in the two echograms is seen in the positions of the ceiling reflections relative to the others.

An architectural reason may explain the low ceilings which seem to be preferred at the stage end of fan-shaped rooms (such low ceilings, usually slope up away from the orchestra, give a ceiling reflection in advance of all others of significance). Visual constancy scaling effects (13) due to the exaggerated perspective of the converging side walls would cause a stage end wall of the height of, say, that in the Vienna Hall to appear enormous in a fan-shaped hall. Consequently, architects prefer abnormally low stage ends in such rooms, in compensation for this effect (see, for example, reference (14), describing the Frederic R. Mann Auditorium, Tel Aviv). Without this compensation, in such halls the players would look remote and tiny in comparison with the room surfaces.

Whatever reason is given, the presence of low surfaces at the point of origin for the ceiling reflection, comparative to the height of the ceiling at the wall-ceiling junction where the "3" reflections originate, and the room width where the corresponding "2" reflections originate, gives rise to an echogram similar to that which would be obtained in a very wide, rectangular hall with a low ceiling.

Changes in height, in the length of the hall, and the slope of various ceiling panels make it very difficult to generalize further, but the author suggests that the method outlined above could be applied with profit to any hall in the prediction of SR. The shape chosen for hall *X* may now be seen to act against the postulate. In a real hall tapered down over the stage, the effect would be more pronounced.

9. REAL HALLS

The ideas presented here may be checked against experience in real rectangular halls. Figure 6 shows the relevant path lengths. The important inequality is that A_2S must be less than P_1S if the ceiling reflection is always to follow the wall reflections. If the height from stage to ceiling is H , hall width W and orchestra width A_0B_0 , then this inequality,

$$A_2S < P_1S,$$

is equivalent to (approximately, ignoring stage height)

$$W + \frac{A_0 B_0}{2} < 2H.$$

When AB is very small (solos or chamber music) W/H is equal to 2. (Note that in this case there may be insufficient sound energy in the reflections to mask reverberation, with attendant confusion: i.e., shorter reverberation time would be desirable.)

As the orchestra width gets greater this ratio must be reduced. For example with orchestral width 40 ft, and $H=60$ ft (typical dimensions for such halls) we find $W=120-20=100$ ft: i.e., $W/H=100/64=1.56$, (allowing 4 ft for the stage height).

This, of course, applies only to central seats on a flat floor and as one moves towards the sides tonal unevenness would be expected until reflections from one side wall clearly predominate. There, however, the full SR would no longer be experienced. Halls with SR in a majority of seats would have to have cross-section ratios very much less than this.

The following rectangular halls which one gathers are generally agreed to have or to

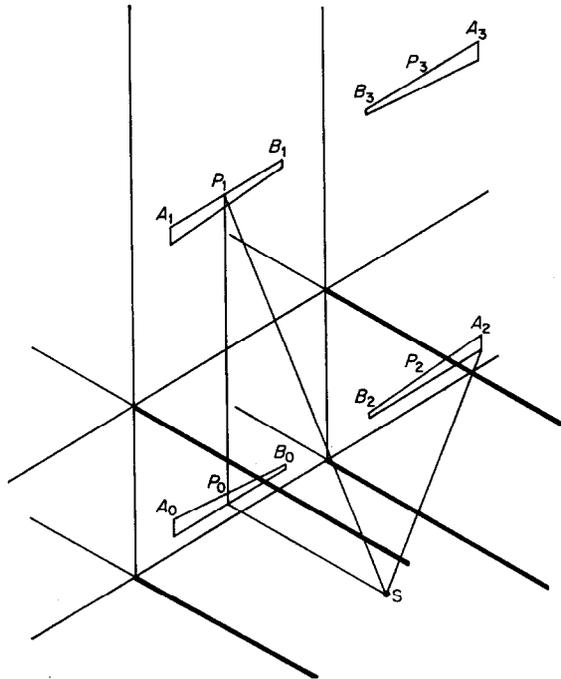


Figure 6. Principal sound paths.

have had SR have the following W/H ratios: Vienna Musikvereinsaal (1:1.10); Boston Symphony Hall (1:1.19); Glasgow St. Andrews (1:1.31); Basel, Stadtcasino (1:1.35); Leipzig Neuesgewandhaus (1:1.30). A similar hall about which there appears to be controversy is the Amsterdam Concertgebouw (15). It has $W/H=1:1.58$, so that for wide orchestral arrangements (greater than 40 ft) it would be over the criterion, while for narrower orchestral arrangements the central seats would experience SR but the remainder would not.

It is not claimed that these figures prove the postulate advanced here but they do seem to lend weight to it. Any further work must inevitably await a comprehensive study of masking by orchestral music such as Seraphim carried out for speech.

ACKNOWLEDGMENTS

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REFERENCES

1. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 6, Kresge Auditorium, M.I.T., Cambridge. New York: John Wiley and Sons Inc.
2. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 6, Benjamin Franklin Kongresshalle, Berlin. New York: John Wiley and Sons Inc.
3. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 6, Tanglewood Music Shed, Lennox, Mass. New York: John Wiley and Sons Inc.
4. R. W. MUNCEY and A. F. B. NICKSON 1960 *C.I.B. Bulletin* Vol. 2, June 1960. A lesson from Australian studies on room acoustics.
5. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 9, Acoustical intimacy. New York: John Wiley and Sons Inc.
6. T. SOMERVILLE (personal communication). The author is indebted to Mr. Somerville for pointing out this fact to him.
7. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 6. New York: John Wiley and Sons Inc.
8. R. H. BOLT, P. E. DOAK and P. J. WESTERVELT 1950 *J. acoust. Soc. Amer.* **22**, 328. Pulse statistics analysis of room acoustics.
9. H. P. SERAPHIM 1961 *Acustica* **11**, 81. Über die wahrnehmbarkeit mehrerer Rückwürfe von Sprachschall.
10. L. L. BERANEK 1962 *Music Acoustics and Architecture*, p. 449. New York: John Wiley and Sons Inc.
11. H. P. SERAPHIM 1961 *Acustica* **11**, 82. Über die wahrnehmbarkeit mehrerer Rückwürfe von Sprachschall.
12. T. SOMERVILLE, C. L. S. GILFORD, N. F. SPRING and R. D. M. NEGUS 1966 *J. Sound Vib.* **3**, (2), 127. Recent work on the effects of reflections in concert halls and music studios.
13. R. L. GREGORY 1966 *Eye and Brain*, p. 151. London: World University Library.
14. L. L. BERANEK 1962 *Music Acoustics and Architecture*. Ch. 6, Frederick R. Mann Auditorium, Tel Aviv. New York: John Wiley and Sons Inc.
15. L. L. BERANEK 1962 *Music Acoustics and Architecture*, p. 365, Concertgebouw Amsterdam. New York: John Wiley and Sons Inc.

APPENDIX (*added in proof*)

A recent visit to Holland and Germany at the invitation of the German Academic Exchange Service enabled the author to discuss the ideas presented here with colleagues at Berlin, Göttingen and Munich, and to experience the sound at a variety of seats in a number of further halls. The following main points arise.

(1) The Concertgebouw, Amsterdam, with chamber wind ensemble and audience only in choir, has SR in most seats on the ground floor. It is suggested that this is due to the highly diffusing ceiling (see sections 8.2 and 9 above). In the balcony increased clarity and reduction of SR were found as predicted, due to the arrival of earlier ceiling reflections at this position, together with relatively stronger direct sound clear of the ground floor seats. Clearly, the closer one sits to the source the higher the level of the direct sound, and consequently the greater the masking of lateral sound due to this alone. This effect was noticeable during an evening concert with full audience at a seat in the centre of the hall 13 rows from the stage.

(2) Even if a hall has a shape which provides a satisfactory arrival order for the reflections, SR will not occur if the main room surfaces, particularly lateral ones, are highly diffusing. The antithesis of SR, aptly described by Mr. Heuwekemeijer, the Manager of the Concertgebouw, as "the feeling of looking at the music", will occur in such halls because the direct sound will have a level very much in excess of each of the multitude of scattered wave fronts such a room must produce. This causes an apparent directionality of the perceived sound. It appears that the masking level is determined by the level of the individual reflections even though in terms of loudness, as Meyer and Schodder showed in 1952, a number of weak reflections are equivalent to a single strong reflection considered by itself. In a room with strong direct sound and many weak reflections the time which elapses between the direct sound and the earliest of the significant following reflections must be considerable due to this masking, and integration will be correspondingly reduced. Once again then, one sees disadvantages in the indiscriminate use of diffusing surfaces. Errors such as unevenness of sound in the room, or echoes, are avoided but SR is impossible too.

(3) Since each of the orchestral images corresponds to a room surface, SR can be achieved in halls with shapes that differ widely from those of classical halls: i.e., the cross-section in question is the effective cross-section relative to the particular seat. This suggests a concert hall in which the audience is subdivided into blocks in the manner of the Berlin Philharmonie but with *every* terrace surrounded by suitable wall and ceiling surfaces. To the author, this appears a major lesson to be learned from the Philharmonie. One can compare strong, clear sound, without SR, in parts of this hall which lack strong lateral sound, with sound with SR in areas towards the rear, where surfaces exist to produce the desired reflections. The difference is marked and to the author wholly convincing. In the former seats one "regards" the music, in the latter one is in it. One notes also that the oblique ceiling produces at the SR seats an overhead reflection with a direction significantly different from that of the direct sound, and thus the undesired masking condition does not occur even though the ceiling image is closer than the wall images at such seats. Both these ideas could be developed architecturally as formal acoustical design determinants.

(4) From preliminary experiments carried out at Southampton and at Göttingen it is evident that the masking due to music depends largely upon the structure of the music. A variety of such masking thresholds have been measured by P. Schubert of Rundfunk- und Fernseh Technik Zentralamt at Adlershof in East Berlin. Space limitations in this Appendix do not allow a discussion of these results, but one can say that although there are considerable quantitative variations from the values for masking assumed earlier in this paper the ideas advanced here remain tenable.