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Basic design techniques to achieve lateral reflections in concert halls

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ABSTRACT

Following the proposal in 1967 that early lateral reflections were desirable for listening to music, Marshall soon realised the virtue of reverse-splay plans for blocks of seating, and the corresponding disadvantage of a fan-shape plan. However relying solely on seating blocks with reverse-splay plans has practical problems, particularly where vertical reflective surfaces are ‘generated’ by raising some individual seating blocks. This difficulty is particularly evident for a music-in-the-round hall. The thesis of this paper is a simple one: that one can not only exploit the 3rd dimension with walls that separate seating blocks but also use overhead reflectors to supply lateral reflections to seating between reverse-splay seating blocks. The discussion will be illustrated by examples of actual concert halls, whose design either promotes early lateral reflections or does not. The classical rectangular hall is of course intermediate between the fan-shape and reverse-splay plan, with the added option of exploiting 2nd order cue-ball reflections off the side walls and balcony soffits. A more complex solution with the goal of providing lateral reflections is to be found in the Philharmonie de Paris of 2015.

Key words: Early lateral reflections, Spatial impression, Concert halls

1. CRITERIA FOR LATERAL REFLECTIONS

The spatial character of reverberant sound is obvious, particularly when the reverberation time (RT) is long. Measuring it is however difficult and the temporal nature of reverberant decays was the first to receive attention (1). The notion of a diffuse sound field in which there is no specific preferred direction must also have been apparent; a diffuse sound field is a necessary condition for the theoretical derivation of the Sabine RT equation. Early investigation of spatial sound dates back to the 1960s; the main tool used then was a simulation system installed in an anechoic chamber. Using anechoic music, the different components of sound were played to a listener at the centre of a loudspeaker array.

In the case of spatial reverberant sound, with the latter available from a reverberation plate and in addition direct sound, it is easy to simulate the transition from unreverberant/clear sound to reverberant/unclear sound. Reichardt and Schmidt (2) found that the direct to reverberant ratio is a good objective measure for this situation. But what about the early reflections? Thiele (3) found that separating sound into early and late parts and calculating the ratio gave a measure of clarity (*Deutlichkeit* in the original German). He proposed 50ms as the boundary between the two parts. Subsequently Reichardt et al. (4) suggested 80ms be used for music.

To return to the question of spatial reverberation, Damaske (5) subsequently showed that a precise equal directional distribution was not necessary for the subjective sense of diffuseness, rather that sound from four orthogonal directions in the horizontal plane around the listener is sufficient.

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The issue of spatial hearing with reverberant sound disappeared from view with theories of spatial hearing related to early reflections after 1967. It was resurrected by Morimoto and Maekawa (6) in 1989 who proposed that there were at least two spatial effects occurring, one linked to early sound and the other to the late. Bradley and Soulodre investigated the latter (7,8), proposing the late lateral energy as a measure of perceived envelopment by sound.

The genesis of the idea of the importance of early lateral reflections came from subjective comparisons between different rectangular concert halls. In 1967, Marshall proposed that early lateral reflections were important for acoustic quality for listeners (9). Using available threshold data for speech (10), he arrived at the conclusion that reflection order was important, that lateral reflections should not be masked by ceiling reflections. In a rectangular space, this leads to the ratio of height-to-width of a hall being important. Marshall termed the effect "spatial responsiveness":

> 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 in it in much the same way that an observer is aware of his involvement with a room he is in.

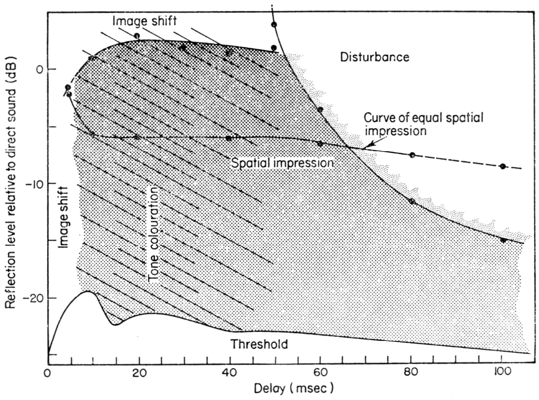

Figure 1. Subjective effects of a single lateral reflection

Barron and Marshall (11) subsequently conducted subjective experiments in a simulation system, which revealed that:

1. the subjective effect of early lateral reflections was easy to perceive, Figure 1.
2. the delay of early lateral reflections was of minor importance
3. the temporal order of reflections from different directions was of very little importance. (Following Marshall's first paper, the thresholds as a function of delay for lateral reflections with music became available (12). These greatly reduced the relative dependence of reflection order with direction.)
4. the directional contribution is according to cos Φ, where Φ is the angle of incidence relative to the axis through the listener's ears
5. bass frequencies are an important component for spatial impression, as highlighted by Marshall
6. the linear magnitude of the subjective effect can be expressed by the early lateral energy fraction:

$$\textbf{Early lateral energy fraction, LF} = \frac{\int_{0.005}^{0.08} p^2(t)\cos^2\theta\, dt}{\int_{0}^{0.08} p^2(t)\, dt} \qquad (1)$$

The average of LF over the four octaves 125, 250, 500 and 1000Hz was proposed. The cosine term in equation (1) is shown squared. This is the directional characteristic of a figure-of-eight microphone used for measurement, whereas the subjective relationship has been shown to be cos Φ. The subjective effect of early lateral reflections is to widen the apparent width of the source; the Apparent Source Width (ASW) can be measured in a laboratory.

An alternative measure for spatial impression is the Interaural Cross-Correlation Coefficient (IACC), which is measured as the peak of the normalised coefficient in the time interval ±1ms (13). The norm is to measure with microphones at the entrance of ear canals of a dummy head. It is clear that subjectively some form of cross-correlation process is involved in establishing an ASW, though the process is more complex than the simple IACC (14). With simplifying assumptions, it is possible to show that LF and IACC are linearly related (15). Bradley (16) found a good relationship when mean hall data is used. A problem with IACC is measurement at low frequencies, where variation of IACC is very small, whereas a difficulty with LF is the relative calibration of the omni- and figure-of-eight microphones.

As mentioned in the quotation from Marshall above (9), there is also a level effect. This was also noted in 1968 by Keet (17). The implications of this for spatial impression were spelt out by Kuhl (18). The sound level for the listener is determined by the dynamic level (pp – ff) produced by the musicians and the gain or Strength at the individual seat location in the hall. If the Strength is high, then a spatial effect can be perceived for quiet music, increasing as the dynamics intensify to fortissimo. On the other hand, in a hall with a low Strength a spatial effect will only be perceived for loud dynamics. In this way, a hall with high Strength offers an exciting growth of the spatial element to an orchestral crescendo.

The acceptable range for LF appears to be 0.10 to 0.35 (19). With values in excess of 0.35, it becomes difficult to concentrate on the direct sound. The subjective spatial effect will be greater in smaller halls, since the Strength is predominantly determined by the inverse of the total acoustic absorption.

No widely accepted combination of the lateral fraction term and level exists. Marshall and Barron (20) have proposed:

$$\text{Degree of source broadening (DSB)} = \text{LF} + (\text{Early level})/60\ , \qquad (2)$$

where early level is measured in decibels.

2. DESIGN IMPLICATIONS

Already in 1968 Marshall proposed some design implications for spatial impression; these were in the light of Schubert's threshold results (21). In addition to H/W, Marshall introduced the effect of the seat dip effect for sound passing over audience seating (22). For higher values of ASW or LF, reflections on paths remote from the audience are desirable.

Barron's experiments removed height as a significant determinant in rectangular halls, leaving width as a significant parameter for spatial impression (23). For halls without parallel side walls, simple geometry shows that ASW is low in a fan-shape hall and potentially high with a reverse splay plan (21), Figure 2. An early proposal by Marshall (24) with a subdivided audience is shown in Figure 3, though it suffers from audience towards the back of the seating blocks being unable to see each other.

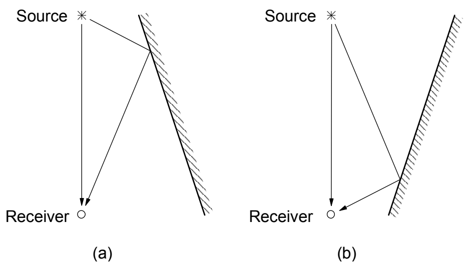

Figure 2. Angle of a lateral reflection in a) a fan-shape plan and b) a reverse splay plan after Marshall (21)

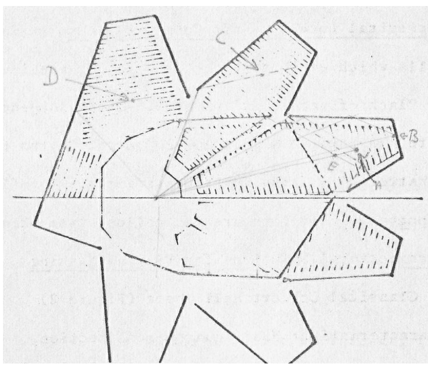

Figure 3. Early proposed design with lateral reflections by Marshall (24).

3. DESIGN IN PRACTICE

The following review of design for spatial impression is mainly chronological. Most auditoria are discussed in more detail in Barron (19).

The early discussion of spatial impression was linked to rectangular halls, with the hall width being an important parameter. Classical rectangular or shoebox halls tend to have horizontal balconies that can introduce second order reflections off the side walls and soffits (often called cue ball reflections) that provide additional early lateral reflections, Figure 4. However many architects have regretted the implication of the rectangular hall that the space is subdivided with the musicians at one end and audience facing them from the other direction.

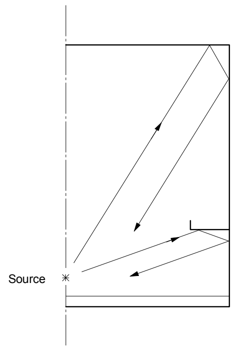

Figure 4. Cross section of a rectangular hall showing 2nd order reflection off side walls and soffits.

The **Berlin Philharmonie** of 1963 predates the proposal that lateral reflections are desirable. This hall represented a radical departure and is the original vineyard terrace hall. The architect, Hans Scharoun, wished to have the performers surrounded by audience. There are two problems linked to this scheme: firstly that many musical instruments are directional, particularly the human singing voice, and secondly that with a large area of uninterrupted audience, there will be few surfaces to provide early reflections. To mitigate the directivity issue, the performing platform was moved towards one end. To introduce early reflections, audience was subdivided into terraces at different heights so that the surfaces that divided them could provide early reflections. Because of its date, some seating areas have reflections arriving laterally and some do not.

For **Christchurch Town Hall, New Zealand**, of 1972, Marshall implemented his proposal of having the first reflection arriving laterally at listeners on paths remote from audience by introducing large reflectors that direct reflections to the neighbouring seating block (25). The plan shape is elliptical, which is notorious for the focussing problems associated with that form. The solution with large reflectors was possible for the gallery seating, but not for the stalls, Figure 5. The subjective response to the hall has been highly favourable. As a personal view, the most remarkable subjective feature in this hall is not the spatial character of the sound (median LF = 0.14) but the sense of intimacy and identification with the performance. With a high degree of clarity, it is possible to listen with ease to individual musical lines. The high clarity might seem unlikely with an occupied RT of 2.35s, however the subjectively significant occupied EDT is estimated to be an acceptable 1.9s; the difference is due to surfaces directing early reflections onto audience.

Figure 5. Christchurch Town Hall, New Zealand.

A further development of the Christchurch design is to be found in the **Michael Fowler Centre, Wellington, New Zealand** of 1983 (median LF = 0.17). The principle difference is the use of Quadratic Residue Diffusers (QRDs) in place of the plane reflectors above gallery level that were used in Christchurch.

The extreme development of the terraced hall is music-in-the-round. One such hall is the **Muziekcentrum Vredenburg** in **Utrecht**, completed in 1979. The acoustic consultants, de Lange and Booy, insisted on vertical planes at different heights in the audience seating, aiming in particular to provide lateral reflections.

It was many years before a hall closely inspired by the Berlin Philharmonie was built, with its subdivided audience areas, separated by high walls. **St David's Hall, Cardiff** in Wales from 1982 is an obvious descendent. However the division lines between audience blocks in this hall are mostly radial to the stage. This is an obvious solution visually, since it does not create blank regions between blocks as found in Figure 3. Measurements of the early lateral energy fraction (median LF = 0.14) indicate that high values (0.24 – 0.30) are to be found where there is a reverse splay, aided in fact by an additional side wall reflection. The lowest values (0.09 – 0.11) occur where no obvious lateral reflection paths exist. It is much easier to design with radial subdivision of audience than with seating blocks bounded by reflecting surfaces able to provide lateral reflections.

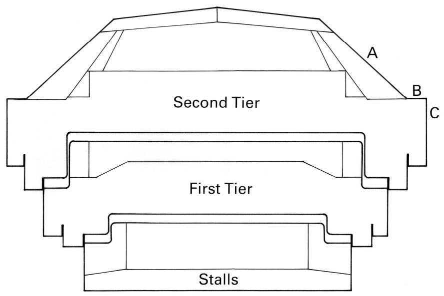

Figure 6. Cross-section through the Royal Concert Hall, Nottingham, looking towards the rear seating. Upper surfaces responsible for lateral reflections are labelled A, B and C (see text).

Another enthusiast from this period for design for spatial impression was Russell Johnson of Artec in New York. His approach to providing lateral reflections was often to modify the cross section. This is well illustrated in the section of his **Royal Concert Hall, Nottingham, England**, which is another hall completed in 1982. Figure 6 shows a typical cross section; the surface A projects a reflection towards the centre of the seating rows, whereas towards the perimeter second-order reflections off the wall C and soffit B provide local reflections. The result is a uniformly high early lateral energy fraction throughout the hall (median LF = 0.23). There is unfortunately a penalty in this case since there was an external height limit imposed on the building, resulting in a reverberation time (mean of 500 and 1000Hz) at the bottom of the acceptable range, namely 1.8s. However by enhancing early reflections the subjectively important early decay time (EDT) is lower than the RT with a mean occupied value of the EDT of around 1.55s.

A very interesting solution to provide lateral reflections was developed by Marshall for **Segerstrom Hall, Orange County Performing Arts Center, California**, which opened in 1986. This 2900 seat hall is multi-purpose with a proscenium stage with a full flying facility. The obvious plan form that this generates is a fan shape but this has a bad acoustic reputation. Starting with a fan shape with a single balcony the modification can be likened to the effect of an earthquake which lowers one side of the auditorium resulting in four audience levels separated by significant vertical surfaces. These surfaces can then generate early lateral reflections, which would have been absent with the original fan shape plan.

The design of the **Chamber Music Hall of the Philharmonie in Berlin** was designed posthumously based on a casual sketch by the architect of the adjacent Philharmonie, Figure 7. It is a music-in-the-round auditorium with seating blocks separated by surfaces that run radially from the stage. As already mentioned above, this poses severe problems for introducing early lateral reflections. The acousticians decided to abandon attempts at uniform early lateral reflections and chose to rely for spatial effects mostly on the later reverberation, which is rendered diffuse by the subdivision of the audience, and by scatterers and suspended reflectors in the ceiling. To this author attending a concert in the space, the absence of spatial impression can be heard in this hall to the slight detriment of the otherwise good acoustics. The hall opened in 1987. Is there a solution to the problem of uniform early lateral reflections for music-in-the-round?

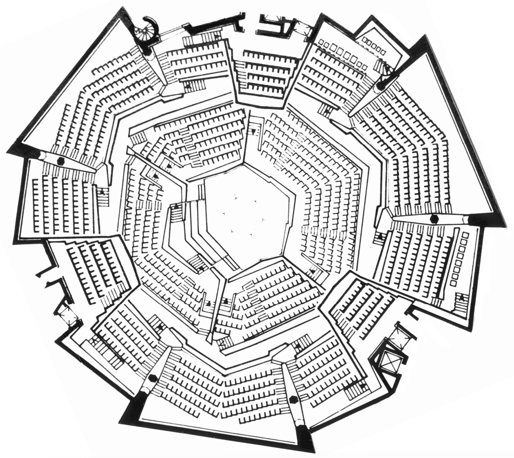

Figure 7. Plan of the Chamber Music Hall of the Philharmonie, Berlin.

An exercise in renovation of fan-shape plans was conducted recently on two identical halls in Alberta, Canada. The **Jubilee Halls in Edmonton and Calgary** date from 1957 had disappointing acoustics for music. Conditions in the second balcony were particularly unsatisfactory. The acousticians Jordan and Rindel (26) installed raised seating sections thereby creating reverse-splay seating areas bounded by vertical surfaces. The same modifications were made in both halls in 2005 and the result has been 'evaluated as very successful'.

The **Philharmonie de Paris** of 2015 was inspired by the experience of the acoustics of the Christchurch hall from 40 years before, even though they appear at first sight very different (27). They both have large seat capacities (2660 and 2400 in Paris). Included in the brief was the requirement for an innovative architectural form. Marshall Day Acoustics introduced two novel features in Paris: a division between inner and outer volumes and an apparently random array of suspended reflectors (often called clouds) to provide early reflections to the audience (28). The subdivision of volumes promotes the sense of reverberation without compromising the proximity of surfaces capable of providing early reflections. The design of the clouds is far from random and together with balcony fronts generates early lateral reflections throughout the audience area, Figure 8. The orientation of these was exhaustively developed with computer programs (principally Rhino and Grasshopper). The response to the acoustics has been enthusiastic.

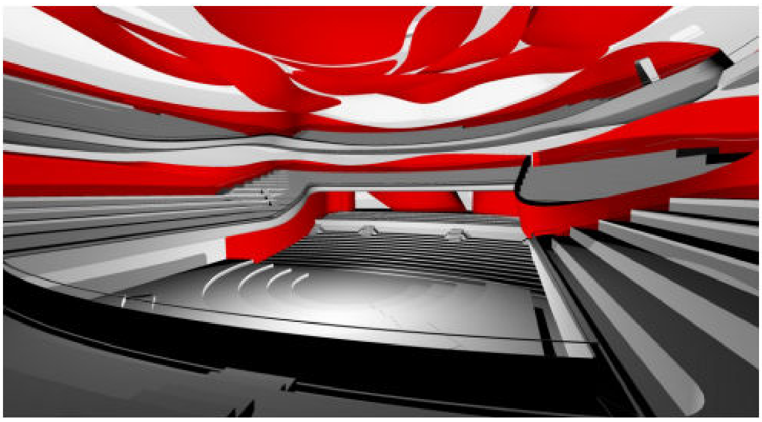

Figure 8. The ensemble of surfaces contributing to the early response for the audience in the Philharmonie de Paris (28).

4. CONCLUSIONS

Early lateral reflections create an Apparent Source Width, which increases with dynamic level. This appears to be a component of the best concert hall acoustics. Apart from being an inevitable attribute of narrow rectangular halls, good spatial impression due to lateral reflections generally requires specific attention to the orientation of surfaces in halls that can provide early reflections.

To return to the problem of early lateral reflections for music-in-the-round as exemplified by the Chamber Music Hall of the Philharmonie in Berlin, there is a solution which employs reverse splay seating blocks with side wall surfaces capable of providing suitable lateral reflections. In between these reverse splay seating blocks are physically higher audience areas which are fed lateral reflections from V-shaped reflectors over the reverse splay seating. The solution in this case is to exploit the vertical as well as the horizontal dimension to provide uniform spatial impression.

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