Considering concert acoustics and the shape of rooms

By Nicholas Edwards

The influence of room shape on the music acoustics of a room is one of the most important questions facing the designers of concert halls, opera houses and other spaces for the performance of music.

Critical listeners often observe that rectangular (shoe-box) rooms have "better" acoustics for music than fan-shaped moms of similar size. Those halls generally accepted as the world's greatest concert halls, such as the Musikvereinssaal in Vienna, the Concertgebouw in Amsterdam, Tonhallesaal in Zurich and Symphony Hall in Boston - are all basically rectangular in plan and section, and would seat audiences of fewer than 2,000 with present day seating standards. This observation, of course, offers no proof of a relationship between room shape and music acoustics, but since the turn of the century some acoustical designers have suspected that there is such a relationship.

In the light of recently acquired knowledge in the field of room acoustics, we can suggest some compelling reasons for the acoustical success of these highly praised older halls, and confirm that there is a close relationship between room shape and "good acoustics" for music.

The science of room acoustics, like many other sciences, has had a somewhat checkered history: at times, the limited knowledge held by its practitioners has led to less than satisfactory rooms for music. One of the earliest applications of acoustical science to the design of rooms for music, however, was a triumph: the opening of Boston Symphony Hall.

The fact that none of the concert halls built since 1905 are yet rated as highly as the best of the older halls, including Boston, might suggest that 19th-century acoustical designers possessed some great secrets of acoustics that they failed to pass on to their successors. It is more likely that fortuitous circumstances engendered by the economy of construction with a rectangular plan and by the structural limitations inherent in traditional building led to such pleasing acoustical results.

Wallace Clement Sabine, the acoustician for the Boston Symphony Hall, wrote that the architects, Mc Kim, Mead and White, had first proposed a fan-shaped room, but that this shaping was abandoned because it had "uncertain merit" as a room for music performance. Sabine had reached his conclusions concerning room shape after receiving comments from musicians and conductors in America and Europe. Following the acoustician's advice, the architects proceeded with the design of a rectangular room. The hall is quite closely based on an older hall on Tremont Street, which was the home of the Boston Symphony Orchestra when Sabine worked on the new design.

Sabine had meticulously investigated the reverberation of sound in rooms and discovered that reverberation is related to the cubic volume of the room and the total sound absorbing power of the room surfaces and contents. On the basis of his work, he proposed the quantification of reverberation time, one of the first quantifiable room acoustics measurements. In the 80 years following Sabine's work on the Boston hall, acousticians and architects have chosen to pay more attention to reverberation time than to the effects of room shape, perhaps because reverberation time was more quantifiable.

Although for many years reverberation time was virtually the only consistently accepted criterion for concert hall design, now, partially through a series of acoustical failures, it is recognized that achieving what is sometimes called the "optimum" reverberation time is no guarantee of good acoustics for music. Some excellent halls have reverberation times well below the "optimum" value, whereas some acoustically poor halls exhibit the "optimum" value.

Since reverberation time criteria have been shown to be unreliable indicators of acoustical quality, acousticians have sought other objective acoustical characteristics that relate more closely to listener preferences. Recent investigations have uncovered such objective characteristics, some of them strongly influenced by room shape.

It has been long known that the characteristics of the "early sound" - that part of the reflected sound arriving within about one quarter of a second of the direct sound - are of importance to listener preference, and this has given acoustical designers some insight into the optimum size of rooms. More recently, scientists involved in independent research programs in different countries have reached a consensus that listener preference relates in many ways to what is currently being called the "lateralization of the sound field" and thus to the shape of rooms.

Increasing the lateralization of sound means increasing the ratio of sound intensity that arrives from the listener's sides (Figures 1, 2, and 8) to that arriving from directions close to the median plane that is to say, from directly in front, behind or above (Figure 6). The ear/brain will integrate that portion of the reflected sound intensity arriving during the first quarter of a second or so after the arrival of the direct sound into one impression of "room sound" so that one is not aware of the individual "arrivals" of sound. This fact suggests rather surprisingly that sound heard directly from the source can reduce the listener preference for symphony music! Needless to say, lateralization is not the only characteristic that affects listener preference; however, the suggestion is perhaps less surprising when one considers that the best acoustics in concert halls are usually found farthest from the stage (in the rear of the top balconies), and that often the worst acoustics are much nearer the stage (the front of the main floor seating area).

We briefly describe here some of the more important studies completed in Europe and Japan:

- Barron (1), in carefully controlled experiments, has shown that the. sensations described as "envelopment" and "warmth" increase with lateralization of the sound field.
- Gottlob (2), reproducing in the laboratory sound fields recorded in existing halls, has discovered a strong positive correlation between lateral sound energy and listener preference.
- Kurozumi and Ohgushi (8) have shown that sound quality, particularly the aural perception of source distance, is dependent on minimizing the similarity of sound at the listener's ears, a phenomenon that occurs when the sound arrives from lateral directions.
- Ando's experiments (4) are designed to find the physical characteristics of optimum sound fields. He has shown that minimizing the similarity of the sounds at the listener's ears, which occurs with maximum lateralization, is required for maximum listener preference.
- Wilkens (5) has suggested that greater loudness is one of the most preferred characteristics of sound fields.
- Blauert (6) has demonstrated the greater sensitivity of the ear (i.e., greater subjective loudness) with lateral sound.

In general, these results show that the positive subjective characteristics of sound fields described as envelopment, warmth, loudness and intimacy are all improved with the increasing lateralization of sound. No researcher has yet found an upper limit to preferred lateralization: maximum listener preference is achieved with maximum lateralization. All these authors have indicated the importance of lateral sound energy. This leads to the question how can greater lateral energy be achieved in the design of a room for music performance.

In order to study the relationship between room shape and sound field lateralization, we have developed a computer program, called IMAGES, that traces the paths traveled by sound "rays" emanating from a source on the stage, reflected from the boundary surfaces of the room, and arriving finally at a particular listener position (Figures 8 and 4).

In the same way as the position of the image resulting from light reflected by a mirror can be found, the computer program we have developed finds the locations of "virtual sources" or "images" of the sound source (Figures 1 and 2). From these image locations, we can trace the paths of the sound

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rays within the room. This computer model has most validity at higher frequencies and with larger room panel surfaces; diffraction, though it can be important in a real room, is not included in the simulation.

A particularly useful analytical tool for studying directional information gained from the computer model is the "soundrose" (Figure 5). The soundrose shows the impulse response of an auditorium in terms of direction and intensity of reflected sound energy. The orientation of the radial lines on the soundrose indicates the direction from which reflected sound waves arrive. The length of a radial line indicates the magnitude of the sound intensity-more precisely, proportional to the component of the logarithm of intensity magnitude in the plane passing through the lateral axis and the listener's line of sight to the source.

For the purposes of the present very general discussion, we can place all angles of incidence into the categories lateral and non-lateral. Non-lateral angles are those close to one's line of sight to the sound source, directly overhead, and centrally behind-i.e., those near the so-called median plane (Figure 6). Lateral angles are perpendicular to non-lateral ones: one's ears are directed toward lateral angles. Sound arriving from directions near the lateral axis contributes most to lateralization. We can generalize that sound arriving from directions within the cones shown in the illustration is lateral sound, and sound arriving from outside the cones is non-lateral.

With the IMAGES computer model, we can demonstrate several common acoustical phenomena found in concert halls. For example, we can study the rear-wall echo found in fan-shaped halls. If the rear wall of a fan-shaped room is reflective, a strong "rear-wall echo" is beard on stage, making conditions for musicians difficult or impossible.

We can demonstrate the genesis of the echo if we study the image locations in Figure 7. Note that the images lie in a circular pattern centered on the stage. Thus, to the performer on the stage, the strength and coherence of the sound returning from the rear wall, the dearth of sound energy between the direct sound and that arriving from the rear wall, and the fact that the echo arrives from the end of the room opposite the performers all combine in the brain to emphasize the disturbing aspects of the echo.

We carried out an analysis of the rear-wall echo in an existing auditorium to study how the room shaping gives rise to the strong echo that is perceived on the stage. From the raytraces, we can see how the architectural boundary surfaces of the room work together in creating the echo. Although the sound reflected from the rear wall directly to the stage contributes to the echo, the greater part of the echo is caused by sound that has been guided to or from the rear wall by the side walls.

In many fan-shaped halls, the echo is suppressed by the application of sound absorptive treatment to the rear wall. This, as we shall see later, is not an altogether satisfactory solution.

A relationship between lateral sound and room shape can be observed in the sequence of diagrams on pages 136 & 137 (Figure 10). The principal architectural variable in this sequence is the angle of the side walls with respect to the center line; this angle varies from 24 deg, for the most fan-shaped room, through 0 deg, for a rectangular room, to -24 deg, for the most reverse-fan-shaped room. The room dimensions are based on a foreshortened Boston Symphony Hall. For simplicity, we have omitted side and rear audience balconies. The sound source is located on the stage near the concert master's position, and the listener is located towards the rear of the main floor. The wall and ceiling surfaces are assumed to be perfect reflectors of sound, and the audience seating area to be a perfect absorber. In order to suppress the rear wall echo discussed above, we have assumed that the rear walls of the more fan-shaped rooms are sound absorptive.

The widest fan-shaped rooms show very little sound arriving from lateral directions. The acoustics in rooms of this shape are usually characterized by a thin, monophonic, distant sound, lacking fullness of tone. The lack of lateral sound in these rooms certainly contributes to their poor acoustics. There are other factors we can observe, too. For instance, musical instruments radiate their sound in very complex patterns: the violin radiates high frequency sound, including bowing noise, in a strongly upward direction, while the instrument's mid-frequency sound radiates predominantly sideways, and low frequency sound in all directions. The precise details of the instrument's radiation characteristics are exceedingly complex and vary from note to note and instrument to instrument (see Meyer, 5 in the list of references, for a more complete treatment of this subject).

For the listener to hear the full timbre of an instrument, the sound radiated in many directions by the instrument must be reflected to the listener. We can observe that the number of sound rays arriving at the listener is affected by room shape. The greater the number of arriving rays and the more spatially even their emanation from the sound source, the greater the efficiency of the room in its task of providing the listener with the full timbre of musical instruments.

A substantially greater number of rays arrive at the listener's position in a rectangular room than in the widest fan-shaped room. We can thus expect to bear a more complete, full timbre in the rectangular room than in the fan-shaped one. This agrees with experience in real rooms having these shapes.

In the rectangular room, we can observe that the sound reaching the listener arrives from many different directions. Note that this occurs even though in the computer simulation we have assumed perfectly flat walls and ceiling without the "sound diffusing" surfaces sometimes said to be necessary for good distribution of sound in a room.

In reverse fan-shaped rooms, there is further lateralization of the sound field, with sound arriving strongly from the listener's left and right. Rooms of this shape offer perhaps the greatest promise for future improvements in concert hall design. It would appear that their potential for lateralization is better even than that of rectangular rooms. Perhaps because of the difficulties in accommodating the audience and performers within this shape, very few such rooms have yet been built. Some examples from antiquity do exist, however, like the Greek theater at Syracuse in Sicily.

The shape of a room influences virtually all aspects of acoustics for music performance. Critical listeners often observe that fan-shaped rooms have acoustical qualities inferior to those in rectangular rooms of similar size. We have reasoned here that the basic differences in plan shaping are in large measure responsible for the differences in sound.

The results of recent research indicate the great importance of lateral sound. We have demonstrated the effects of room shaping on lateral sound energy and other acoustical characteristics. Thus acoustical science is moving towards a closer agreement with those musicians and critical listeners who have long observed the superior acoustics of rectangular rooms.

Perhaps most exciting is the prospect of improving on the "best" acoustics currently found in rectangular rooms with designs embodying relatively untried reverse fan-shaping. It may now be possible to design new concert halls that have better acoustics than the Musikvereinssaal, the Concertgebouw or Boston Symphony Hall.

Wallace Clement Sabine is known mostly for his studies of reverberation time. But it is to his credit that he did not rely solely on his ability to calculate reverberation time in the acoustical design of Symphony Hall, Boston. The importance of his greatest contribution to music performance - a hall with rectangular shape - has been for the most part ignored.

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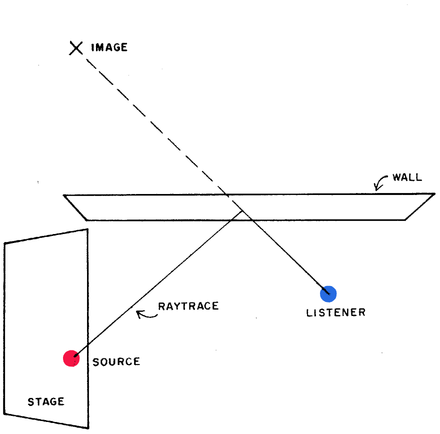

Figure 1

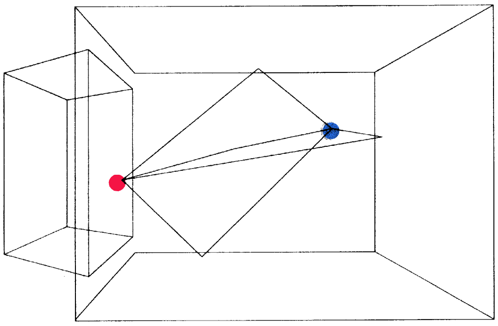

Figure 2

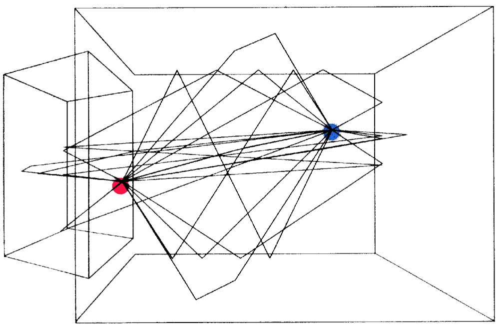

Figure 3

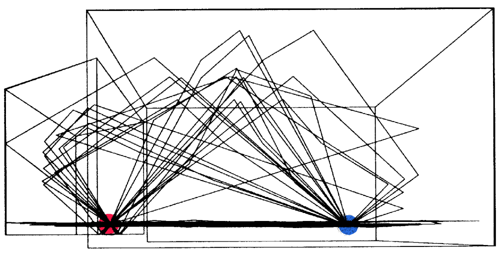

Figure 4

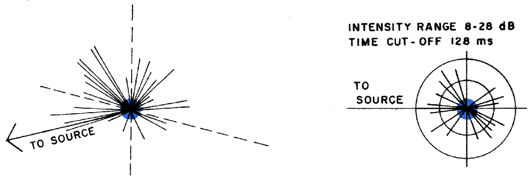

Figure 5

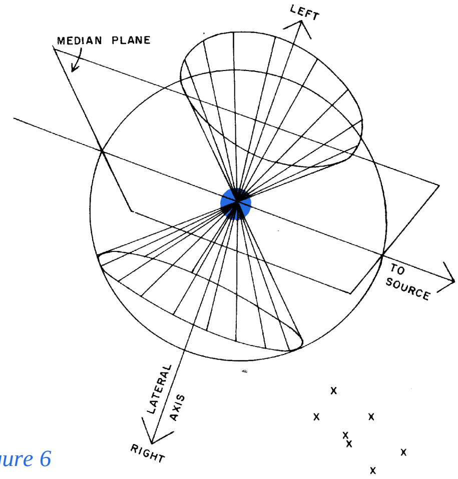

Figure 6

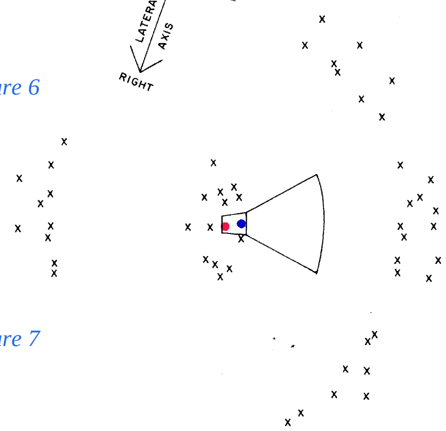

Figure 7

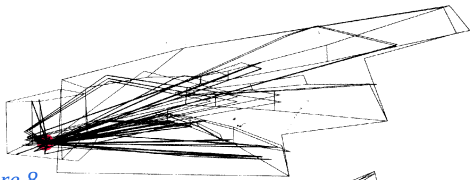

Figure 8

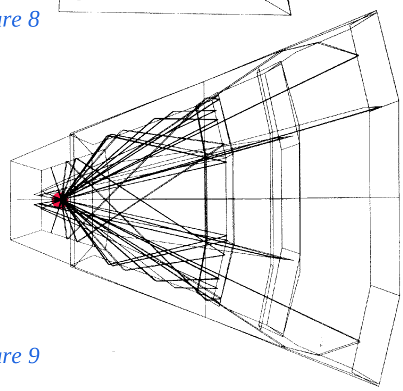

Figure 9

In a hypothetical room plan showing only a single boundary wall, sound emanating from the source is reflected by the side wall to the listener, and the path taken by the sound wave is indicated by the raytrace (Figure 1). The computer constructs the raytrace by first locating the image of the source - that is, the apparent source of reflected sound; the distances between sound and listener and between image and listener represent the time it takes for sound to travel from source and from image to the listener. In Figure 2, raytraces show the sound reflected only once by the boundary surfaces of a rectangular room. When raytraces show sound reflected more often, their pattern grows more dense and complex (Figure 3). Further there are ceiling reflections seen clearly only in section (Figure 4). These raytraces show ceiling and "cornice" reflections, the latter constituting sound reflected near the junction of walls and ceiling. Raytraces in both plan and section show sound reflected many times by boundary surfaces in the room. The soundrose, shown here in both perspective and plan (Figure 5), depicts the direction and the magnitude of intensity of reflected sounds as they arrive individually to the listener. Because the lateral and non-lateral components of sound are of most interest acoustically the plan projection of the soundrose is often the most informative. The lateral axis of sound passes into the listener's ears, while the median plane passes vertically through the center of the head in the direction of the listener's sightline to the sound source (Figure 6). In general sound arriving from directions falling within the two 9O deg cones shown on the lateral axis contribute the most to lateralization. Sound that arrives in the median plane - i.e., directly in front, above, below and behind the listener - does not contribute to lateralization. With both sound source and listener on stage, as two musicians listening to each other would be, the images constructed by computer for a fan shaped room lie in a circular pattern centered on the stage (Figure 7). From the listener's perspective, sound from these images will arrive at the ears at about the some time, but will be separated from the arrival of direct sound. In a fan-shaped room, this phenomenon is perceived as an echo from the rear wall. Raytraces, generated here for an existing auditorium (Figures 8 and 9), are associated with an echo observed on the stage and show how the side walls work in conjunction with the long rear wall surface to "focus" the echo on stage.

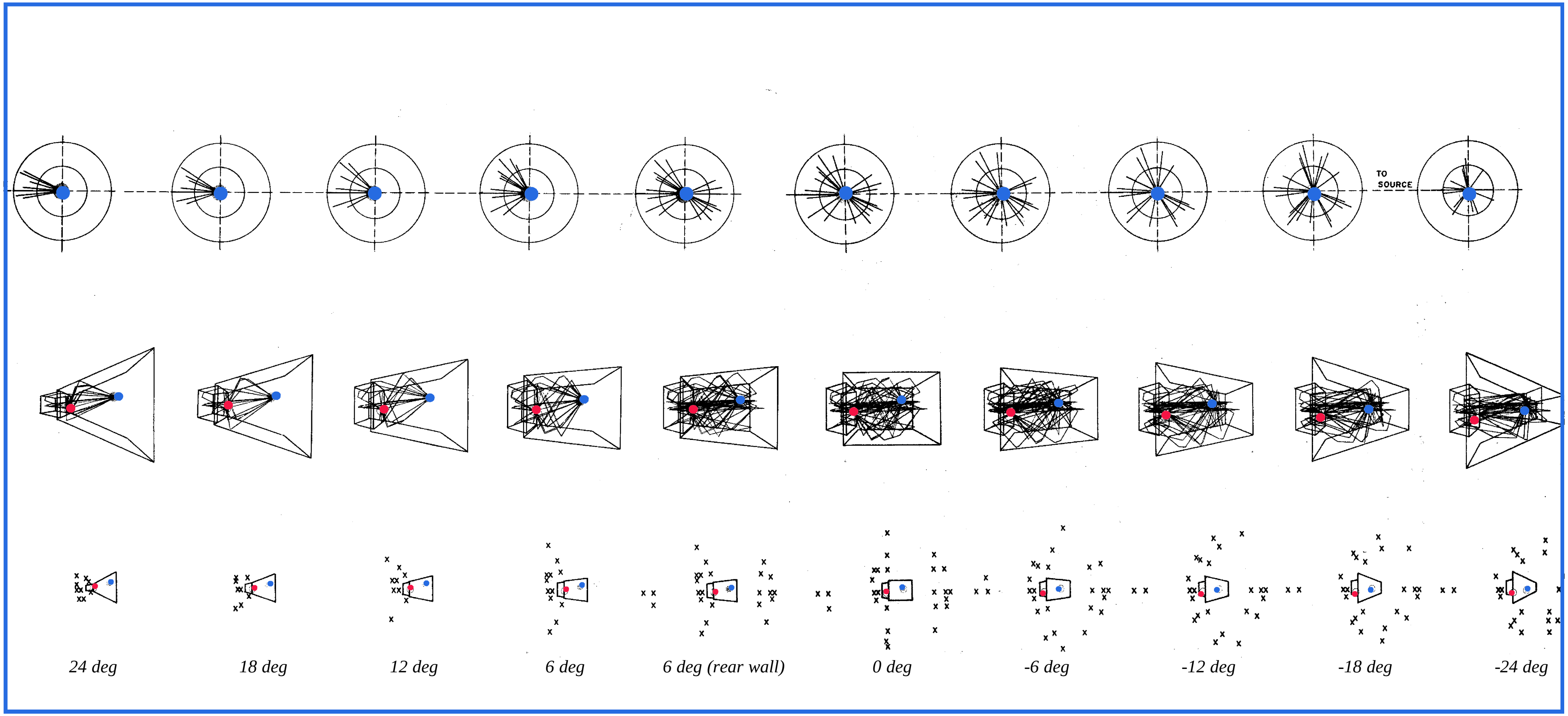

Figure 10

The three sequences shown here depict sound arriving at a listener in 9 different rooms, ranging from acutely fan-shaped to acutely reverse fan-shaped - that is to say, side walls at one extreme splay from the stage at 24 deg, and at the other extreme approach convergence near the rear wall at -24 deg. The depictions use three different descriptive methods: soundroses at the top, raytraces at the middle, and images at the bottom. As room shape changes from fan-shaped to rectangular (the room with parallel walls angled at 0 deg), sound arriving at the listener becomes more lateralized. (The projected raytraces seen in the plans above include sound reflected from the ceiling and cornices, as well as sound from the side walls.) Whereas the listener receives almost no lateral sound in the widest fan-shaped rooms, lateralization increases as room shapes progressively approach the rectangular. It is the multiplicity of these lateral reflections that allow the listener such pleasurable musical perceptions as warmth, envelopment and richness of sound. (One must remember that these drawings describe sound patterns for only one hypothetical combination of source and listener; the patterns will change as listeners and sources change positions.)
In reverse fan shaped rooms, sound arriving at the listener is even more lateralized than in rectangular rooms. Moreover, many sound images are evenly distributed around the listener, from behind and above as well as from in front. Such rooms offer perhaps the greatest promise for future improvements in concert hall design