The acoustics of concert halls
Bradley, J. S.; Soulodre, G.

Publisher's version / Version de l'éditeur:

Physics World, 10, May 5, pp. 33-36, 1997-05-01

The acoustics of concert hall

NRCC-43994

Bradley, J.S.; Soulodre, G.

May 1997

A version of this document is published in / Une version de ce document se trouve dans:
Physics World, 10, (5), May, pp. 33-36, May 01, 1997

features

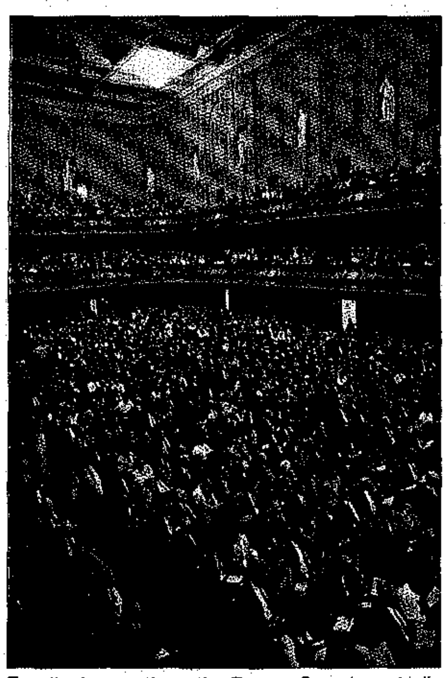
Some concert halls are renowned for their sound quality. The latest acoustics research is finding out what makes the difference, and could help in the design of future auditoria

The acoustics of concert halls

JOHN BRADLEY AND GILBERT SOULODRE

THE most important characteristic of any concert hall must be the sound that it delivers to the listener. While the acoustics of a hall are unlikely to make a good orchestra sound bad, a well designed auditorium can provide a truly memorable experience. Yet the Boston Symphony Hall, which opened in 1900, was the first to be designed with the science of acoustics in mind.

Wallace Sabine, a physicist from Harvard University, was engaged as the scientific consultant for the new hall. Sabine had already discovered the key relationship between the "reverberation time" – essentially the time it takes for reflected sounds to die away to inaudibility – and the sound absorption and volume of the room. The Boston Symphony Hall was designed with this equation in mind, and today it is recognized as one of the best concert halls in the world.



Excellent acoustics – the Boston Symphony Hall.

The reverberation time is still a key measure of room acoustics, and it must be adequate for a concert hall to be successful. Since Sabine's work, however, more complex equations have been developed and optimum reverberation times have been prescribed for a variety of conditions. These typically depend on the room volume, the frequency of sound, and whether the source of the sound is music, speech or some other type of performance.

Reverberation time provided the first objective indicator of acoustic quality, which is intrinsically subjective. We now know, however, that there is more to room acoustics, and in particular concert hall acoustics, than simply achieving the correct reverberation time. A key goal of acoustics research has therefore been to derive further objective measures of the effects that combine to form our subjective impression of a room's acoustics.

A more complete understanding of concert hall acoustics has gradually emerged since the 1950s. Many studies have made use of simulated sound fields, which attempt to mimic the sound heard in a concert hall (see box). The simulated fields can be switched rapidly, allowing the acoustic conditions to be changed at will. This enables the listener to make more reliable subjective judgements of the sound quality.

Early reflections hold the key

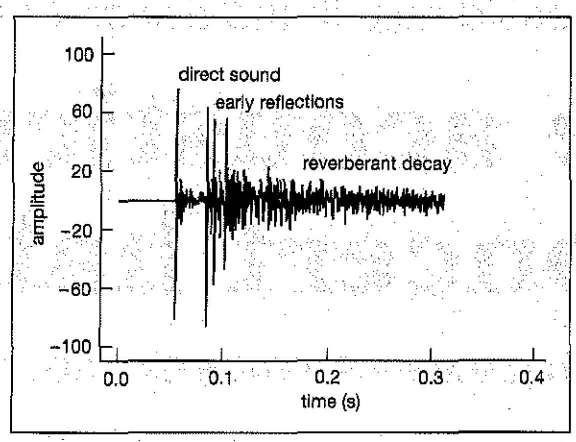
Studies in the 1950s showed that "early reflections" are highly significant for sound quality. To understand this, imagine a very short or impulsive burst of sound, such as a hand clap or a gun shot, in a concert hall. The sound pulse is reflected many times in the room, and different reflections arrive at a listener at different times. The sequence of reflected pulses that arrive at a given position in the room is called an impulse response and it is indicative of how all sounds will behave in the room.

The sound pulse that travels directly from the source to the listener arrives first (figure 1) and this "direct sound" typically has the largest amplitude. It is followed after a short gap by several discrete reflections, and their arrival times, amplitudes and directions of arrival depend on the geometry of the room. Reflections continue to arrive for some time; the amplitudes tend to decrease exponentially, resulting in a reverberant decay. The reverberation time is defined as the time taken for the total sound amplitude to decrease by 60 decibels – a factor of 10^6 in intensity – after the generation of the sound has stopped.

When the direct sound is strong relative to the reverberant energy, which is the sum of the reflected sound energy, the perceived clarity and definition of speech or music will be high. Conversely, high levels of reverberant energy cause successive words or musical notes to blend into each other, and in extreme cases the music or speech can sound "muddy".

Early reflections are important because they can enhance the direct sound. Helmut Haas, while studying at the University of Göttingen in Germany in the late 1940s, showed how a single early reflection influences our perception of speech. More complex experiments with multiple early reflections showed that our hearing system does not identify these reflections as separate events. We instead integrate the direct sound together with all of the energy in the 50–80 ms after its arrival. Early reflections effectively reinforce the direct sound and therefore increase the clarity and definition of the room's acoustics, particularly since they often include a significant portion of the sound energy in the impulse response.

Walter Reichardt at the Technical University in Dresden, Germany, suggested that these ideas could be used to provide an objective measure of the perceived clarity of music. This measure is the ratio of the energy in the first 80 ms of the impulse response to the energy that arrives later.



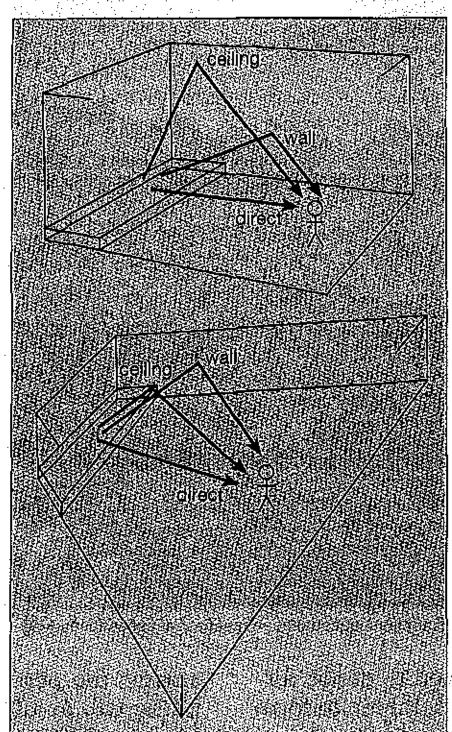
1 The first part of the response of a concert hall to a short impulsive burst of sound initially shows a large-amplitude signal corresponding to the direct sound, which travels directly from the source to the listener. Discrete early reflections follow a short time later. Reflections continue to arrive with decreasing amplitudes, resulting in a reverberant decay.

At about the same time, it was found that the "early decay time" – now usually measured to be the time for the amplitude to decrease by 10 decibels – is more relevant to subjective judgements of reverberance than the conventional reverberation time, which largely relates to the physical properties of the room. Although measured early decay times and reverberation times can be quite similar, large differences can indicate unusual acoustical conditions.

The effect of the room on the overall sound level and the loudness of individual sounds is another important factor in concert-hall acoustics. Although reverberation times tend to be nearly constant throughout a hall, most other acoustical measures vary from seat to seat because of variations in early reflections. It is important to limit these variations to avoid large differences in sound quality.

The measures described so far – the overall sound level, energy ratios and decay times – represent effects that can be heard with a single ear. These "monophonic" measures are recorded by a single microphone that records sounds from all directions, so they ignore any perceptual effects that relate to the direction in which the sound is travelling when it is heard.

The direction and time of arrival of specific reflections are determined by the geometry and architectural features of the room (figure 2). The shape of the hall is particularly important. Most early concert halls, such as the Boston Symphony Hall, tended to be rectangular and shaped like a shoe box, but fan-shaped halls have gained in popularity because more people can sit close to the stage. In a rectangular hall the first reflections, and hence the strongest, usually arrive from the side walls. But these reflections are often relatively weak in a fan-shaped hall, where the strongest reflection typically comes from the ceiling. Furthermore, the shape of the hall affects the angle at which the reflections arrive at the listener. The acoustics of the two types of hall are thus quite different.



2 In a rectangular "shoe-box" hall the sound reflected from the wall arrives before that reflected from the ceiling. The opposite is true for a fan-shaped hall, and these differences affect a listener's perception of the sound.

In the late 1960s researchers began to appreciate that the direction of arrival of early reflections affected the perception of sound. Harold Marshall of the University of Auckland in New Zealand was the first to suggest that early lateral reflections – those that arrive from the side – could be particularly important. Michael Barron, then at the University of Southampton in the UK, found that these early lateral reflections provide an increased sense of "spaciousness", also known as spatial impression. This is a subjective quantity, and Barron suggested that increased spaciousness should provide two desirable effects: a stronger impression of being in a room or an indoor space; and an apparent widening of the source.

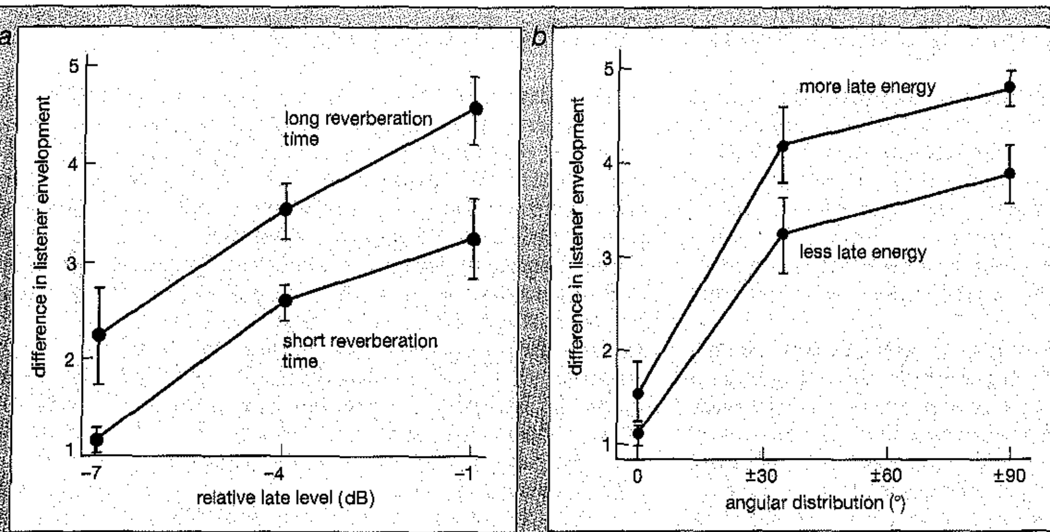
It was soon accepted that strong early reflections from the side walls are a vital component of a successful concert hall. Many designers, including Marshall, incorporated large side-wall reflectors into new concert halls, an advance that allowed them to consider many new shapes.

What is spaciousness?

At the time of Barron's work, spaciousness was not clearly defined and many different subjective descriptions were attributed to the terms spaciousness and spatial impression. Spaciousness could mean, for example, the broadening of the source, the "envelopment" of the listener in the sound, or even the envelopment of the source. Researchers usually assumed that these different perceptions of spatial impression were affected only by early lateral reflections, and it was not until the 1990s that other elements of the impulse response were explored. This recent work has led to a more complete picture of spatial impression in concert halls.

In the early 1990s Masayuki Morimoto and colleagues at Kobe University in Japan helped to define two different subjective effects that combine to provide a sense of spatial impression. First, the apparent width of the source can be increased by making the early lateral reflections stronger. This is because our hearing system tends to combine the early reflections with the direct sound, and strong reflections from the side give a certain ambiguity to the position of the source.

Second, the listener can feel surrounded by the sound, a perception



3(*a*) Experiments show that the feeling of listener envelopment is greater for long reverberation times (red line) than short ones (green). It also rises as the amount of energy in late-arriving reflections is increased. (*b*) The sense of listener envelopment is also enhanced when the late-arriving sound comes from more lateral directions. The green line shows the response when there is more late energy in the sound field, and the red line is for lower levels of late energy.

now known as listener envelopment. We have recently shown that this feeling is only created if strong lateral reflections arrive at later times. This could explain the findings of earlier studies – which suggested that an increased sense of spaciousness was related to longer reverberation times – because longer reverberation times would tend to correlate with increased reverberant (late arriving) sound coming from the sides of the room.

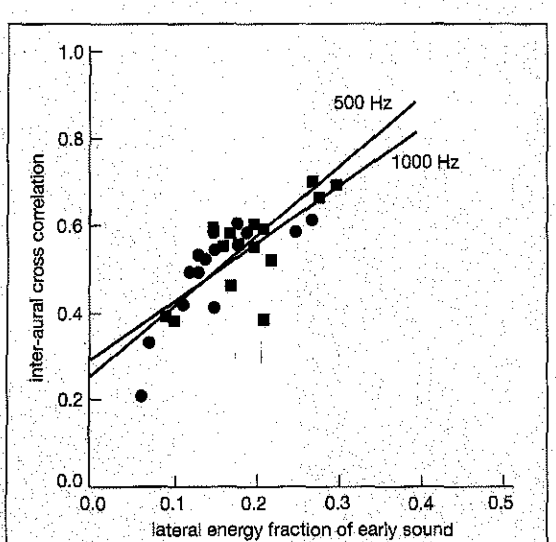
Our exploration of late-arriving lateral reflections has shown that they have two major effects. They do provide an increased sense of listener envelopment, but they also make it more difficult to detect the effects of early reflections. We investigated this last effect in the laboratory by asking listeners to identify the change in the apparent source width between pairs of sound fields. The sound fields were simulated using an array of loudspeakers: each loudspeaker produced a specific reflection plus some reverberant energy, and these individual signals combined to generate the sound field (see box).

When the reverberant energy in the sound field was reduced to zero, people could accurately detect the changes in the apparent source width. However, when reverberant energy was present, they found it more difficult to judge the effects of early reflections on the apparent width of the source. Further experiments showed that increasing levels of reverberant energy caused people to be less sensitive to the changes in early reflections. Since the reverberant energy is often quite strong in real rooms, it can mask these effects of early lateral reflections.

It therefore appears that late-arriving lateral reflections could be more important than early reflections for spatial impression in concert halls. Earlier experiments may have overestimated the importance of early reflections because the sound fields usually did not include any reverberant energy.

The other, more important, effect of late-arriving lateral reflections is to provide a sense of being enveloped or immersed in the sound. We performed experiments in which people rated the difference in listener envelopment between a reference sound field, with a low perceived level of listener envelopment, and the sound field under test. Judgements were made on a 5-point scale, where 1 represented no difference and 5 represented the maximum expected increase in listener envelopment. The tests show that the perception of listener envelopment increases as more energy is contained in late-arriving reflections and as these reflections are delayed further in time – in other words, for longer reverberation times (figure 3*a*). The experiments also indicate that listener envelopment is enhanced when the late-arriving sound comes from more lateral directions (figure 3*b*).

It is clear that spatial impression is made up of two subjective effects. More early lateral reflections increase the apparent width of the source, mainly because they are perceptually integrated with the direct sound. Later-arriving reflections are not combined with the direct sound and their individual directions of arrival cannot be easily identified, which leads to a sense of listener envelopment.



4 Average values of the inter-aural cross correlation and the lateral energy fraction of the early sound were measured for 15 concert halls. The data shown by the green squares were measured at a frequency of 1000 Hz, and the other data were measured at 500 Hz. The lines show the best fit to the data and indicate that the two measures are strongly related.

Measuring our perceptions

We have looked at subjective impressions of spaciousness, but how can these perceptual quantities be measured objectively? In the early 1970s Barron and Marshall introduced the "lateral energy fraction", which measures how much of the early-arriving sound comes from lateral directions. This measure has been found to correlate well with subjective judgements of the apparent source width.

Barron also suggested that the lateral energy fraction should be related to another measure of the early sound, the "inter-aural cross correlation". This is the correlation between the two impulse responses measured by microphones in the two ears of an artificial head, and essentially measures the similarity of the early sound

Concert hall sounds in the laboratory

It is very difficult for people to compare the sound quality of two different concert halls because such intrinsically subjective judgements can be influenced by many different factors. Laboratory tests using simulated sound fields can help the listeners to reach more reliable judgements. This is because the sound field can be switched almost instantly, allowing a more precise comparison of different acoustic conditions.

There are two main ways of simulating sound fields in the lab, and both have their advantages and limitations. One method is to surround the listener with an array of loudspeakers. Each loudspeaker reproduces a different signal, and each signal contains one or more discrete reflections plus a reverberant decay. The amplitude, time of arrival and frequency content of each component in the signal can be precisely controlled using a variety of digital signal-processing devices. Changes to the sound field can be made almost instantaneously, allowing different sound fields to be compared. This type of experiment is performed in an "anechoic chamber", which has walls that absorb as much sound as possible (figure *a*). The simulated sound fields are not corrupted by reflections in the test room.

This method has the advantage that each parameter of the sound field can be precisely controlled, which allows researchers to assess the effect of varying a single acoustical parameter while the others are kept constant. Moreover, listeners are able to turn their heads, enabling them to more naturally consider how the direction of arrival might affect the sound. The main problem is that the realism of the reproduced sound fields is limited by the number of loudspeakers and independent signal channels that are used.

The other simulation method provides more realistic sound fields. This approach is based on "binaural simulation", which tries to recreate the same sounds at both ears of the listener as would be heard in a concert hall. This is achieved using an artificial head with two microphones fitted in the ears. The impulse response – the sound field created by a short burst of sound – is then recorded by both microphones and the responses are combined to give the binaural impulse response.

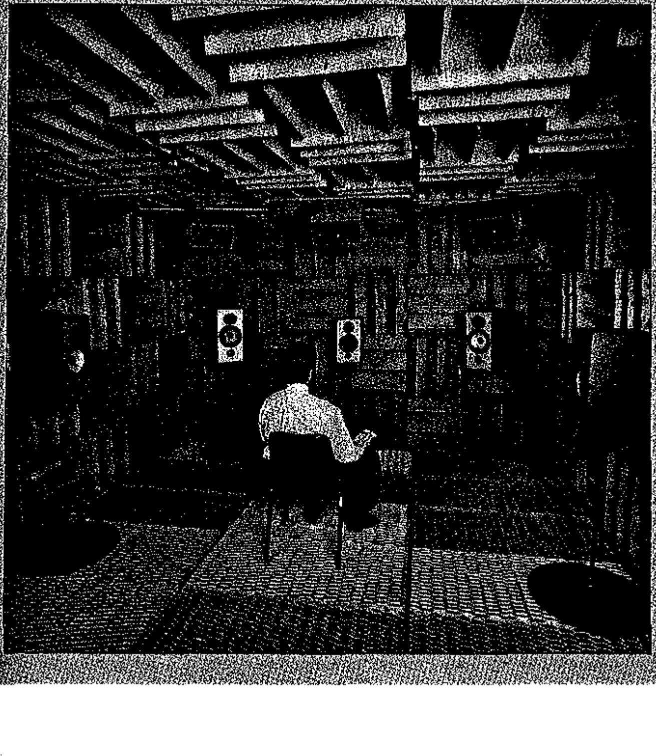
The binaural impulse response is measured at various positions in a concert hall. These responses are convolved with music that has been recorded in an anechoic room to simulate the sound of the music at different positions in the concert hall. The binaural impulse responses can also be edited to some extent, allowing the effects of certain acoustical parameters to be investigated.

The resulting sound fields can be reproduced through headphones or loudspeakers, although headphones can make it more difficult to identify the direction of the source of the sound. For example, sounds often appear to be located inside the listener's head, and sounds that originate in front of the listener can seem to come from behind.

Loudspeakers overcome this problem but introduce two new challenges. First, an anechoic chamber is needed to prevent the sound fields from becoming corrupted. Second, loudspeakers produce acoustic cross-talk: the left ear can hear sounds intended for the right ear and vice versa. Both of these problems can be overcome by using a loudspeaker configuration proposed by one of us (GS). In this set up the loudspeakers are placed close to the listener, avoiding the need for an anechoic room, and mechanical barriers are used to reduce cross-talk (figure *b*).

The key advantage of binaural simulation is that more realistic sound fields, as recorded in concert halls, can be generated. Its main drawback is that the control a researcher can have over the sound fields is more limited. The ideal solution is therefore to use both methods to explore fully the subjective effects of various acoustic measures. □

a



b