Acoustics and Psychoacoustics Applied - Part 1: Listening room design

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So far in this book we have considered acoustics and psychoacoustics as separate topics. However, real applications often require the combination of the two because although the psychoacoustics tells us how we might perceive the sound, we need the acoustic description of sound to help create physical, or electronic, solutions to the problem.

The purpose of this chapter is to give the reader a flavor of the many applications that make use of acoustics and psychoacoustics in combination. Of necessity these vignettes are brief and do not cover all the possible applications. However, we have tried to cover areas that we feel are important, and of interest.

The level of detail also varies but, in all cases, we have tried to provide enough detail for the reader to be able to read, and understand, the more advanced texts and references that we provide, and any that the reader may discover themselves, for further reading. The rest of this chapter will cover listening room design, audiometry, psychoacoustic testing, filtering and equalization, public address systems, noise reducing headphones, acoustical social control devices, and last, but by no means least, audio coding systems.

7.1 CRITICAL LISTENING ROOM DESIGN
Although designing rooms for music performance is important, we often listen to recorded sound in small spaces. We listen to music, and watch television and movies, in both stereo and surround, in rooms that are much smaller that the recording environments. If one wishes to evaluate the sound in these environments then it is necessary to make them suitable for this purpose.

In Chapter 6 we have seen how to analyze existing rooms and predict their performance. We have also examined methods for improving their acoustic characteristics. However, is there anything else
we can do to make rooms better for the purpose of critically listening to music? There are a variety of approaches to achieving this and this section examines: optimal speaker placement, IEC rooms, room energy evolution, LEDE rooms, non-environment rooms, and diffuse reflection rooms.

7.1.1 Loudspeaker arrangements for critical listening
Before we examine specific room designs, let us first examine the optimum speaker layouts for both stereo and 5.1 surround systems. The reason for doing this is that most modern room designs for critical listening need to know where the speakers will be in order to be designed. It is also pretty pointless having a wonderful room if the speakers are not in an optimum arrangement.

Figure 7.1 shows the optimum layout for stereo speakers. They should form an equilateral triangle with the center of the listening position. If one has a greater angle than this the center phantom image becomes unstable — the so-called "hole in the middle" effect. Clearly, having an angle of less than 60° results in a narrower stereo image.

![Optimal stereo speaker layout](image)

**FIGURE 7.1** Optimal stereo speaker layout.

5.1 surround systems are used in film and video presentations. Here the objective is to provide both clear dialog and stereo music and sound effects, as well as a sense of ambience. The typical speaker layout is shown in Figure 7.2.
FIGURE 7.2 Typical speaker layout for 5.1 surround.

Here, in addition to the conventional stereo speakers there are some additional ones to provide the additional requirements. These are as follows:

- **Center dialog speaker**: The dialog is replayed via a central speaker because this has been found to give better speech intelligibility over a stereo presentation. Interestingly the fact that the speech is not in stereo is not noticeable because the visual cue dominates so that we hear the sound coming from the person speaking on the screen even if their sound is coming from a different direction.
- **Surround speakers**: The ambient sounds, and sound effects, are diffused via rear mounted speakers. However they are, in the main, not supposed to provide directional effects and so are often deliberately designed, and fed signals, to minimize their correlation with each other and the front speakers. The effect of this is to fool the hearing system into perceiving the sound as all around with no specific direction.
- **Low-frequency effects**: This is required because many of the sound effects used in film and video, such as explosions and punches, have substantial low-frequency and subsonic content. Thus, a specialized speaker is needed to reproduce these sounds properly. Note: this speaker was never intended to reproduce music signals, notwithstanding their presence in many surround music systems.

More recently systems using six or more channels have also been proposed and implemented; for more information see Rumsey (2001).

As we shall see later the physical arrangement of loudspeakers can significantly affect the listening room design.

**IEC listening rooms**

7.1.2 IEC listening rooms

The first type of critical listening room is the IEC listening room (IEC, 2003). This is essentially a conventional room that meets certain minimum requirements: a reverberation time that is flat, and between 0.3 and 0.6 seconds above 200 Hz, a low noise level, an even mode distribution and a
recommended floor area.

In essence this is a standardized living room that provides a consistent reference environment for a variety of listening tasks. It is the type of room that is often used for psychoacoustic testing as it provides results that correlate well with that which is experienced in conventional domestic environments. This type of room can be readily designed using the techniques discussed in Chapter 6.

However, for critically listening to music mixes, etc. something more is required and these types of room will now be discussed. All of them don't only control reverberation, but also the time evolution and level of early reflections. They also all take advantage of the fact that the speakers are in specific locations to do this and very often have an asymmetric acoustic that is different for the listener and the loudspeakers.

Although there are many different implementations, they fall into three basic types: reflection controlled rooms, non-environment rooms, and diffuse reflection rooms. As they all control the early reflections within a room we shall look at them first.

### 7.1.3 Energy"time considerations

A major advance in acoustical design for listening to music has arisen from the realization that, as well as reverberation time, the time evolution of the first part of the sound energy build-up in the room matters, that is, the detailed structure and level of the early reflections, as discussed in Chapter 6. As it is mostly the energy in the sound that is important as regards perception, the detailed evolution of the sound energy as a function of time in a room matters.

Also there are now acoustic measurement systems that can measure the energy"time curve of a room directly, thus allowing a designer to see what is happening within the room at different frequencies, rather than relying on a pair of "golden ears." An idealized energy"time curve for a typical room is shown in Figure 7.3.

![Figure 7.3 An idealized energy"time curve.](image)

It has three major features:

- A gap between the direct sound and first reflections. This happens naturally in most spaces and
gives a cue as to the size of the space. The gap should not be too long — less than 30 ms — or the early reflections will be perceived as echoes. Some delay, however, is desirable as it gives some space for the direct sound and so improves the clarity of the sound, but a shorter gap does add “intimacy” to the space.

- The presence of high-level diffuse early reflections, which come to the listener predominantly from the side, that is, lateral early reflections. This adds spaciousness and is easier to achieve over the whole audience in a shoebox hall rather than a fan-shaped one. The first early reflections should ideally arrive at the listener within 20 ms of the direct sound. The frequency response of these early reflections should ideally be flat and this, in conjunction with the need for a high level of lateral reflections, implies that the side walls of a hall should be diffuse reflecting surfaces with minimal absorption.

- A smoothly decaying diffuse reverberant field which has no obvious defects, and no modal behavior, and whose time of decay is appropriate to the style of music being performed. This is hard to achieve in practice so a compromise is necessary in most cases. For performing acoustic music a gentle bass rise in the reverberant field is desirable to add “warmth” to the sound but in studios this is less desirable.

**Reflection-controlled rooms**

**7.1.4 Reflection-controlled rooms**

For the home listener, or sound engineer in the control room of a studio, the ideal would be an acoustic that allows them to "listen through" the system to the original acoustical environment that the sound was recorded in. Unfortunately the room in which the recorded sound is being listened to is usually much smaller than the original space and this has the effect shown in Figure 7.4.

![Amplitude vs Time Graph](image)

**FIGURE 7.4** The effect of a shorter initial time delay gap in the listening room.

Here the first reflection the listener hears is due to the wall in the listening room and not the acoustic space of the sound that has been recorded. Because of the precedence effect this reflection dominates, and the replayed sound is perceived as coming from a space the size of the listening room, which is clearly undesirable.

What is required is a means of making the sound from the loudspeakers appear as if it is coming from a larger space by suppressing the early reflections from the nearby walls, as shown in Figure 7.5.
Examples of this approach are: "live end dead end" (LEDE) (Davies and Davies, 1980), "Reflection free zone" (RFZ) (D'Antonio and Konnert, 1984), and controlled reflection rooms (Walker, 1993, 1998). One way of achieving this is to use absorption, as shown in Figure 7.6.

The effect can also be achieved by using angled or shaped walls, as shown in Figures 7.7 and 7.8.
This is known as the "controlled reflection technique" because it relies on the suppression of early reflections in a particular area of the room to achieve a larger initial time delay gap. This effect can only be achieved over a limited volume of the room unless the room is made anechoic, which is undesirable.
The idea is simple: by absorbing, or reflecting away, the first reflections from all walls except the furthest one away from the speakers the initial time delay gap is maximized. If this gap is larger than the initial time delay gap in the original recording space then the listener will hear the original space, and not the listening room.

However, this must be achieved while satisfying the need for even diffuse reverberation, and so the rear wall in such situations must have some explicit form of diffusion structure on it to assure this. The initial time delay gap in the listening should be as large as possible, but is clearly limited by the time it takes sound to get to the rear wall and back to the listener. Ideally this gap should be 20 ms but it should not be much greater or it will be perceived as an echo. In most practical rooms this requirement is automatically satisfied and initial time delay gaps in the range of 8 ms to 20 ms are achieved.

Note that if the reflections are redirected rather than being absorbed, then there will be "hot areas" in the room where the level of early reflections is higher than normal. In general it is often architecturally easier to use absorption rather than redirection, although this can sometimes result in a room with a shorter reverberation time.

**The absorption level required for reflection-free zones**

7.1.5 The absorption level required for reflection-free zones

In order to achieve a reflection-free zone it is necessary to suppress early reflections, but by how much? Figure 7.9 shows a graph of the average level that an early reflection has to be at in order to disturb the direction of a stereo image.

![Graph showing the absorption level required for reflection-free zones](image)

**FIGURE 7.9** The degree of reflection suppression required to assure a reflection-free zone (data from Toole, 1990).

From this we can see that the level of the reflections must be less than about 15 dB to be subjectively inaudible. Allowing for some reduction due to the inverse square law, this implies that there must be about 10 dB, or $\alpha = 0.9$ of absorption on the surfaces contributing to the first reflections.
In a domestic setting it is possible to get close to the desired target using carpets and curtains, and bookcases can form effective diffusers, although persuading the other occupants of the house that carpets, or curtains, on the ceiling is chic can be difficult. In a studio more extreme treatments can be used. However, it is important to realize that the overall acoustic must still be good and comfortable, that it is not anechoic, and that, due to the wavelength range of audible sound, this technique is only applicable at mid to high frequencies where small patches of treatment are significant with respect to the wavelength.

7.1.6 The absorption position for reflection-free zones
Figure 7.10 shows one method of working out where absorption should be placed in a room to control early reflections.

![Figure 7.10: The image method for controlled reflection room absorption placement.](image)

By imagining the relevant walls to be mirrors it is possible to create “image rooms” that show the direction of the early reflections. By defining a reflection-free space around the listening position, and by drawing "rays" from the image speaker sources, one can see which portions of the wall need to be made absorbent, as shown in Figure 7.11.
This is very straightforward for rectangular rooms, but a little more complicated for rooms with angled walls. Nevertheless, this technique, can still be used. It is applicable for both stereo and surround systems, the only real difference being the number of sources.

In Figure 7.11 the rear wall is not treated because normally some form of diffusing material would be placed there. However, absorbing material could be so placed, in the places determined by another image room created by the rear wall, if these reflections were to be suppressed.

One advantage of this technique is that it also shows places where absorption is unnecessary. This is useful because it shows you where to place doors and windows that are difficult to make absorptive.

To minimize the amount of absorption needed one should make the listening area as small as possible because larger reflection free volumes require larger absorption patches. The method is equally applicable in the vertical as well as the horizontal direction.

**Non-environment rooms**

**7.1.7 Non-environment rooms**

Another approach to controlling early reflections, which is used in many successful control rooms, is the "non-environment" room. These rooms control both the early reflections and the reverberation. However, although they are quite dead acoustically, they are not anechoic.

Because for users in the room there are some reflections from the hard surfaces, there are some early reflections that make the room non-anechoic. However, sound that is emitted from the
speakers is absorbed and is never able to contribute to the reverberant field. How this is achieved is shown in Figure 7.11.

These rooms have speakers, which are flush mounted in a reflecting wall, and a reflecting floor. The rear wall is highly absorbent, as are the side walls and ceiling.

The combined effect of these treatments is that sound from the loudspeakers is absorbed instead of being reflected so that only the direct sound is heard by the listener, except for a floor reflection. However, the presence of two reflecting surfaces does support some early reflections for sources away from the speakers. This means that the acoustic environment for people in the room, although dead, is not oppressively anechoic.

Proponents of this style of room say that the lack of anything but the direct sound makes it much easier to hear low-level detail in the reproduced audio and provides excellent stereo imaging. This is almost certainly due to the removal of any conflicting cues in the sound, as the floor reflection has very little effect on the stereo image.

These rooms require wide-band absorbers as shown in Figure 7.12.

![Figure 7.12](image)

**FIGURE 7.12** A non-environment control room. Shaded areas are wide-band absorbers (from Newell, 2008).

These absorbers can take up a considerable amount of space. As one can see in Figure 7.12, the
absorbers can occupy more than 50% of the volume. However, it is possible to use wide-band membrane absorbers, as discussed in Chapter 6, with a structure similar to that shown in Figure 6.48 with a limp membrane in place of the perforated sheet. Using this type of absorber it is possible to achieve sufficient wide-band absorption with a depth of 30 cm, which allows this technique to be applied in much smaller rooms whose area is approximately 15 m². Figure 7.13 shows a typical non-environment room implementation: “The Lab”, at the Liverpool Music House.

Because non-environment rooms have no reverberant field, there is no reverberant room support for the loudspeaker level, as discussed in Section 6.1.7. Only the direct sound is available to provide sound level.

In a normal domestic environment, as discussed in Chapter 6, the reverberant field is providing most of the sound power and is often about 10 dB greater than the direct sound. Thus in a non-environment room one must use either 10 times the power amplifier level, or specialist loudspeaker systems with a greater efficiency, to reproduce the necessary sound levels (Newell, 2008).

The diffuse reflection room

7.1.8 The diffuse reflection room

A novel approach to controlling early reflections is not to try to suppress or redirect them, but instead diffuse them. This results in a reduced reflection level but does not absorb them.

In general most surfaces absorb some of the sound energy and so the reflection is weakened by the reflection. Therefore the level of direct reflections will be less than that which would be predicted by the inverse square law, due to surface absorption.

The amount of energy, or power, removed by a given area of absorbing material will depend on the energy, or power, per unit area striking it. As the sound intensity is a measure of the power per unit area this means that the intensity of the sound reflected is reduced in proportion to the absorption coefficient. Therefore the intensity of the early reflection is given by:
\[ I_{\text{direct sound}} = \frac{[QW_{\text{Source}}(1 - \alpha)]}{4\pi r^2} \] \hspace{1cm} (7.1)

From the above equation (7.1), which is Equation 1.18 with the addition of the effect of surface absorption, it is clear that the intensity reduction of a specular early reflection is inversely proportional to the distance squared.

Diffuse surfaces on the other hand scatter sound in other directions than the specular. In the case of an ideal diffuser the scattered energy polar pattern would be in the form of a hemisphere. A simple approach to calculating the effect of this can be to model the scattered energy as a source whose initial intensity is given by the incident energy.

Thus, for an ideal scatterer, the intensity of the reflection is given by the product of the equation describing the intensity from the source and the one describing the sound intensity radiated by the diffuser. For the geometry shown in Figure 7.14 this is given by:

\[ I_{\text{diffuse reflection}} = \left( \frac{W_{\text{Source}}}{4\pi r_s^2} \right) \times \left( \frac{2}{4\pi r_d^2} \right) \] \hspace{1cm} (7.2)

![Diagram of sound reflection](image)

**FIGURE 7.14** The geometry for calculating the intensity of an early reflection from a diffuse surface.

The factor 2 in the second term represents the fact that diffuser only radiates into half a hemisphere and therefore has a “Q” of 2. From Equation 7.2 one can see that the intensity of a diffuse reflection is inversely proportional to the distance to the power of four. This means that the intensity of an individual diffuse reflection will be much smaller than that of a specular reflection from the same position.

The diffuse reflection room (cont.)

So diffusion can result in a reduction of the amplitude of the early reflection from a given point. However, there will also be more reflections, due to the diffusion, arriving at the listening position from other points on the wall, as shown in Figure 7.15.
Surely this negates any advantage of the technique? A closer inspection of Figure 7.15 reveals that although there are many reflection paths to the listening point they are all of different lengths, and hence time delay. The extra paths are also all of a greater length than the specular path, shown dashed in Figure 7.15.

Furthermore the phase reflection diffusion structure will add an additional temporal spread to the reflections. As a consequence the initial time delay gap will be filled with a dense set of low-level early reflections instead of a sparse set of higher level ones, as shown in Figure 7.16. Of particular note is that, even with no added absorption, the diffuse reflection levels are low enough in amplitude to have no effect on the stereo image, as shown earlier in Figure 7.9.
cause. This is due to both the reduction in amplitude due to the diffusion and the smoothing of the comb filtering caused by the multiplicity of time delays present in the sound arriving from the diffuser. As these comb filtering effects are thought to be responsible for perturbations of the stereo image (Rodgers, 1981), one should expect improved performance even if the level of the early reflections is slightly higher than the ideal.

The fact that the reflections are diffuse also results in an absence of focusing effects away from the optimum listening position and this should result in a more gradual degradation of the listening environment away from the optimum listening position. Figure 7.17 shows the intensity of the largest diffuse side wall reflection relative to the largest specular side wall reflection as a function of room position for the speaker position shown. From this figure we can see that over a large part of the room the reflections are less than 15 dB below the direct sound.

**FIGURE 7.17** The intensity of the largest diffuse side wall reflection 3.5 relative to the direct sound as a function of room position; contours are in dB.

Figure 7.18 shows one of the few examples of such a room.
The experience of this room is that one is unaware of sound reflection from the walls: it sounds almost anechoic, yet it has reverberation. Stereo and multi-channel material played in this room has images that are stable over a wide listening area, as predicted by theory. The room is also good for recording in as the high level of diffuse reflections and the acoustic mixing it engenders, as shown in Figure 7.15, helps to integrate the sound emitted by acoustic instruments.

Summary
In this section we have examined various techniques for achieving a good acoustic environment for hearing both stereo and multi-channel music. However, the design of a practical critical listening room requires many detailed considerations regarding room treatment, sound isolation, air conditioning, etc. that are covered in more detail in Newell (2008).

Coming up in Part 2: Pure-tone and speech audiometry.

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