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Creating Acoustic Space

Abstract

Perception of the acoustic environment places all sound events in a three-dimensional soundfield, surrounding us wherever we are and changing as we move through acoustic space. Creating music for electronic reproduction requires a detailed understanding of sound in space, how it evolves over time, how it interacts with the physical space and how acoustic space itself may become a compositional tool. This paper will review human spatial perception and the physical parameters that must be understood and controlled to create clarity, depth, spatial impression and envelopment in an electro-acoustic recording, with particular reference to multi-channel surround reproduction environments. Methods for creating natural, or even unnatural, acoustic spaces in a recording will be presented. It will consider why some listening environments significantly influence the creation or perception of acoustic space while others may be relatively benign.

Introduction to Spatial Perception

Every sound event occurs in a three-dimensional physical space and the auditory perception of the event by a listener is influenced by the acoustic characteristics of that space, even outdoors where the only physical characteristic may be the ground. From the listener's perspective, the event will have a location defined by a vector from the listener to the source with an azimuth angle on the horizontal plane defining front/rear and left/right, an angle of elevation defining above or below and a distance parameter, see Figure 1.

Our ability as a listener to resolve these parameters of azimuth, elevation and distance has been carefully analysed by many researchers, including [8] and [13], and indicates a high degree of accuracy in azimuth detection in the frontal arc, reduced azimuth accuracy for the rear arc and further reduced accuracy for elevation detection. For repeating sounds, accuracy is significantly improved when there is an opportunity for head turning, to provide our brain with increased processing time to gather more information and a different set of parameters for comparison. The psycho-acoustic and physical parameters associated with location perception include interaural differences of time, amplitude and spectrum (ITD, IAD, ISD), and ear pinna effects to resolve front/rear and elevation locations.

Distance perception, in the absence of visual information, is often more difficult to establish with any degree of accuracy as the listener relies on subtle changes in amplitude and frequency spectrum combined with variations in acoustic reflections from surrounding objects.

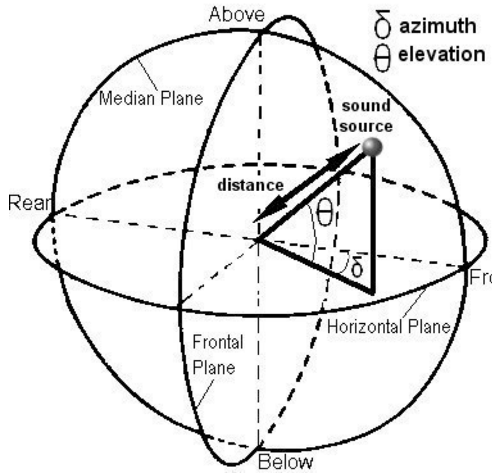

Figure 1. *Location of a sound source*

Acoustic Reflections

A sound event also takes place over time, with a start and end time for the event. In our physical space, there are acoustic reflections caused by the radiating sound pressure waves striking surfaces in the space and bouncing back to the listener. These reflections occur after the start of the sound event, at times dictated by the speed of sound (approximately 340 meters per second) and the distance from the source to the reflecting surface and from there to the listener.

The acoustic properties of the reflections are defined by amplitude and spectral differences from the source, arrival time after the start time of the source and the direction of the reflection, and the total of all reflections is broadly described as reverberation. All reflections will be quieter than the source due to energy lost at the reflecting surface and energy loss through the air. When a sound event lasts for a certain period of time, reflections are still generated continuously from the start but will be masked by the direct sound to some extent during the event.

This so called running reverberation [10] may be masked but may still cause timbral changes to the direct sound by spectral interference. However, reverberation becomes very clear after the end of the sound event, and in the gaps between sound events, where the reflections continue to arrive at the listener and are no longer masked by the direct sound. The amplitude, spectral and time characteristics of reverberation have been the subject of intense analysis by many researchers, including [4], [7] and [11], seeking to understand the perceptual response of listeners to reverberation. It is clear that reverberation affects the clarity of a sound event, the blend between multiple sound events, the perceived depth of the soundfield and the sense of envelopment in a soundfield.

Time Divisions in Reverberation

The broad definition of reverberation covers all reflections caused by a sound event in space, but there are different perceptual characteristics depending on their arrival time after the direct sound. Before we can consider constructing a suitable acoustic space for any recording or composition, we must deconstruct the parameters of acoustic space and understand how they contribute to our perception of acoustic environments.

There are three principle parts to our perception of spatial impression: the **direct** sound coming line-of sight from the sound source to the listener; **early reflections**, within approximately 80 milliseconds of the start of the event, which are the first individual reflections coming from the closest surfaces in the room; and **late reverberation** which is the multiple reflections from many surfaces, coming later in time as the sound bounces around the room. Each component plays an important part in our perception of the sound event in space, with the direct sound identifying the location of the source and its distance from the listener.

Room Impression

The first reflections to arrive will come from the closest reflecting surfaces in the acoustic space. In a 'normal' room with a rectangular floor plan and a height dimension different to width and length, there will be six single reflections from the six room surfaces, all called first order reflections. There will also be strong reflections via two surfaces to the listening position, called second order reflections, which will take longer to arrive and be quieter than first order reflections, see Figure 2. Third and higher order reflections bounce off three or more surfaces before arriving at the listening position.

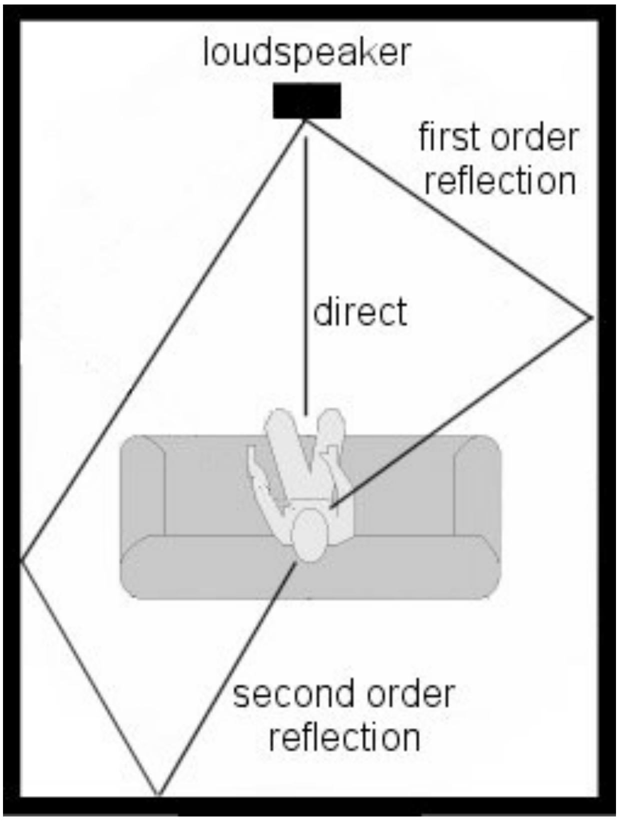

Figure 2. *First and Second Order Reflections in a room.*

Research into human auditory perception has grouped together the multiple low order reflections which occur less than 80ms after the direct sound as the early reflections (ERs). The early reflections create our perception of the room itself, our room impression, as they are first reflections from each room surface, including the walls, floor and ceiling. Their time of arrival and their strength relative to the direct sound indicate the distance to the surfaces and they provide some indication of the surface materials, whether they are hard or soft, flat or irregular. The angle of arrival may also be perceived and provides direction information for the walls and other reflecting objects. If, for example, there was no wall on one side, the lack of reflections would clearly indicate to the listener the openness in that direction.

The Diffuse Soundfield

Late reverberation consists of multiple reflections coming after 80ms and assists in perception of the size of the space and the absorption characteristics of the surface materials and objects in the space. Since these late reflections are generated by multiple reflections from many surfaces travelling longer distances, they are progressively quieter and eventually reduce in loudness until inaudible. Since there are many possible paths to the listening position via multiple reflections, there may be many thousands of late reflections depending on the size of the room and the nature of the reflecting surfaces.

The time taken for these late reflections to reduce in loudness to 60dB below the level of the direct sound is known as the reverberation time, RT. With the multiple reflections comes a significant change in spectral characteristics, with high frequencies reducing in loudness more quickly than low frequencies, known as spectral damping. The reflections which constitute late reverberation come from all directions around the listening position, usually with no dominant direction, providing a diffuse soundfield.

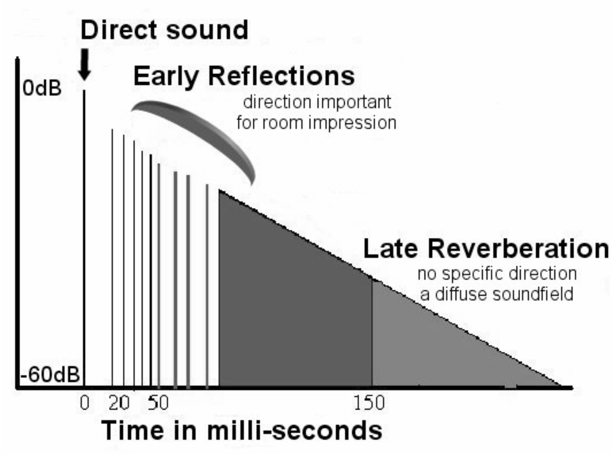

Figure 3. *Direct, Early Reflections and Late Reverberation.*

Distance and Depth Perception

Our ability to perceive the distance to a sound source is influenced by our knowledge of the spectral characteristics of the source, as we identify subtle variations in amplitude and timbre as the distance to a source changes. We also rely on changes in reflection patterns to enhance depth perception, and it has been shown that reflections between 10ms - 50ms assist our perception of depth without affecting the clarity of the source, particularly not influencing the intelligibility of speech. However, reflections between 50ms – 150ms, while contributing to our perception of depth, also degrade the timbre of the source and the intelligibility of speech, reducing clarity and introducing muddiness.

It has been shown through research by Barbara Shinn-Cunningham that we adapt quickly to room characteristics [14] particularly bad acoustics, where significant sonic degradation becomes inaudible after about ten minutes. It becomes easy to believe the acoustics are satisfactory, making it easy to enjoy a musical performance in a poor acoustic environment.

Reverberation Masking

Reverberation in a listening environment is often perceptually masked for many different reasons. The presence of a strong, continuous direct sound will mask the running reverberation which will almost always be quieter. Musically this would occur where there are sustained sound clusters, particularly when they have wide spectral characteristics. Any reverberation, whether early or late reflections, will only be clearly audible when there are gaps between sound events, so the transient structure is important in our perception of reverberation. It has also been shown that the perceived loudness of the reverberation is greatest when there are longer gaps between sound events, [11].

Masking is also pitch dependent, as large jumps in pitch will reveal reverberation more clearly, even during sustained sound events. As the onset time of reverberation is dependent on the size of the acoustic space, a large space will have a longer initial delay before the first reflections and also a longer delay until late reverberation begins. This is referred to as pre-delay, and where the pre-delay is longer, it will improve the audibility of late reverberation, unmasking the reverberation temporally.

Masking is also dependent on the reverberation time, which is clearly related to the tempo of the music. When the tempo is fast, a shorter RT will be more audible, while a longer RT may suit a slower tempo. Reverberation may also be unmasked spatially, when reflections are clearly separated laterally or vertically from the direct sound.

Unmasking Reverberation

The different techniques used to unmask reverberation are described in table 1:

Temporal	time intervals between sound events
Pitch	large pitch variations reveal reverb on previous notes
Pre-delay	increasing the time before reverb starts
Tempo	reverb time RT short for fast tempo, may be longer for slow tempo
Spatial	lateral reflections are separated from the direct sound

***Table** 1. Unmasking Reverberation*

Critical Distance

The pattern of direct, early reflections and late reverberation will be very different at different locations in an acoustic space, particularly as the listening position moves away from the source. Close to the source, the direct sound will always be loudest. As the distance to the source increases, the loudness of the direct sound decreases, early reflections change direction and also decrease in loudness, but the loudness of the diffuse late reverberation stays relatively constant. However, there is a specific distance from the source at which the direct sound and the late reverberation are equally loud, known as the Room Radius or Critical Distance.

Within the critical distance, direct sound and early reflections dominate perception, but beyond the critical distance, there is no clear direction for the source and loudness remains relatively constant for the rest of the space. In a large performance venue, this distance may be as close as three to five metres from the source. Beyond this point, while the direct sound is not providing a perception of the location of the source, visual source location dominates perception and provides an anchor to the source. Distance perception is assisted by the perception of the ratio between direct sound and reverberant sound, but this ratio is most effective within the critical distance.

Performance Venues

Musical performances using only acoustic instruments take place in architectural spaces selected for acoustic properties which will enhance the enjoyment of listeners and performers. Analysis of these spaces by Beranek, Ando and others, [1], [3] and [4], have revealed the objective acoustic characteristics which have led to subjective critical acclaim of many venues throughout the world, and were detailed by the author in a paper to ACMC 2004 in Wellington [2]. Analysis included assessments of spaciousness, clarity, reverberation warmth and character, and acoustic support for the performer.

Key architectural characteristics included an initial time delay before the first reflection arriving at the listener of around 20 milliseconds, (20ms) and many reflective surfaces to provide as many different reflection paths as possible, producing highly diffuse late reverberation. In addition, Beranek suggested that there should be very little high frequency absorption in the hall to aid brilliance in the sound, that the most important lateral reflections occur between 35°-75° from the front centre, and that any overhead reflections will add texture, especially when lateral reflections are low.

The initial time delay of 20ms will be the onset time for early reflections and requires a first order reflection path of about 6.8 metres greater than the direct path. This would correspond to a hall width of about 14 metres for a listener seated 10 metres from the sound source.

Embedded Acoustic Space

However, the subjective quality of a performance venue depends on the style of music performed, and the majority of the venues analysed by Beranek are used for classical music written primarily before the early part of the twentieth century, which still remains a significant proportion of the performance repertoire of many orchestra and chamber music groups. It is certainly true that when chamber music is performed in very large venues, designed for orchestral performances and a financially viable audience, the listening experience is degraded by the reverberation characteristics of the venue.

While live performance is an important listening experience, recordings of classical music have very wide usage in broadcasting, film scores and personal listening and provide a solid financial base for many musicians. These recordings usually take place in venues with appropriate acoustic characteristics to enhance the music, and using the skills of the audio engineer, the reverberation characteristics are embedded in the final recording. There is often critical acclaim for the spatial acoustic qualities of the recording, including the width of the sound image, the depth of the sound field and the overall spatial impression. However, these embedded spatial qualities bear no relationship to the acoustic characteristics of the listening environment. Is it possible for a normal listener at home to hear these spatial qualities, or are they modified by the listening acoustic environment?

Which Space Are We Listening To?

A typical home listening environment would be a room approximately 4 metres by 3.5 metres, with a ceiling height of 3 metres, although exact dimensions will vary considerably. Ear height would generally be about 1 metre from the floor, loudspeaker height similarly one metre and the distance between listener and loudspeaker about 3 metres, shown in Figure 4. In this situation, the path length differences between the direct sound and the six first reflections from walls , floor and ceiling would be about two metres longer from side walls and the ceiling, about one metre longer from the front and rear walls and about 0.6 metres longer via the floor. This would introduce first reflections at intervals of 1.76ms, 2.94ms and 5.88ms. These reflections would generally be strong as home design currently favours flat bright surfaces.

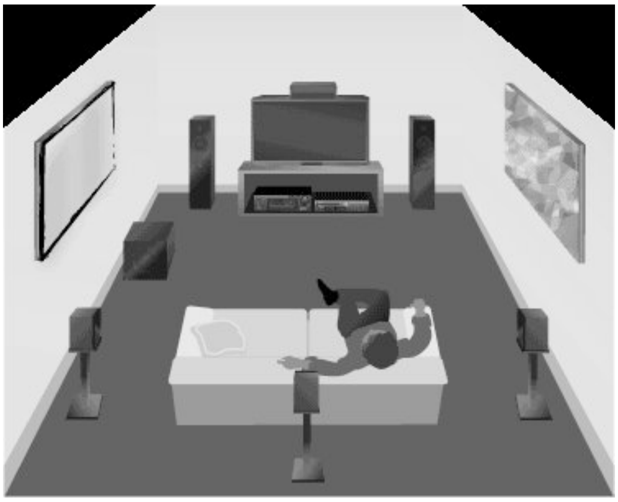

Figure 4. *Typical home listening room showing short path length reflections from walls and floor*

However, the reflections are very much earlier than those considered ideal for lateral early reflections in performance venues. In fact, research into auditory perception shows that reflections within about 50ms of the direct sound merge with the direct sound to become changes in timbre or apparent source size, with the precedence effect dictating that all the reflections are frontal, positioned around the direct sound [9]. Therefore, while these very early reflections will influence the spectral response or timbre at the listening position due to comb filtering, they will not be separated from the direct sound by a listener as early reflections. The late reverberation characteristics of this room would be reveal a short reverberation time of about 300ms – 400ms, with damping caused by soft furnishings and body absorption.

Consequently, the influence of a small listening room on audio reproduction will be mainly timbral changes with very little sense of room impression and no spatial envelopment in a diffuse soundfield. Also, the critical distance in most home listening environments is very short, probably less than one metre from the loudspeakers, which will also tend to diminish the influence of the room on audio reproduction, beyond timbral changes. Therefore, the dominant acoustic space will be that embedded in the recording.

Composing with Acoustic Space

For composers of electro-acoustic music, utilizing sounds generated by electronic devices including computers and hardware synthesizers, it is rare that a recording will be made utilizing the acoustic characteristics of a large performance venue. Even when acoustic instruments are incorporated into a composition, they are more likely to be recorded in the controlled acoustic environment of a recording studio or home studio, where reverberation generated by the acoustic space is usually reduced or excluded from the recording using close microphone techniques.

The resulting electro-acoustic sounds which form the compositional palette are therefore characterized as close and direct, with no spatial characteristics embedded in their original form. Through the process of composition, they are assembled into the musical form desired with consideration given to pitch, timbre, amplitude and duration.

The Mixing Space

The realization of the composition as a final recording will require the mixing together of the various sound sources. Decisions will be made about loudness and timbral balance and any spatial characteristics to be incorporated, including location in the soundfield of the final recording and any attempt to place the individual sounds in an acoustic space. The acoustic characteristics of this mixing environment will significantly influence the decisions made, and are more important than the acoustics of any listening environment. If the physical dimensions of the mixing room are small, there will be short path lengths for reflections at the listening position which will cause timbral changes. Attempts to compensate for these timbral changes will be embedded in the final mix, but the sound will change when heard in another room. To overcome these problems requires the mixing room to be highly absorbent at the locations on the walls where first order reflections will occur. Sound absorbing panels need to be mounted behind the loudspeakers, at the sides and above the listening positions and on the rear wall to stop first order reflections, see Figure 5.

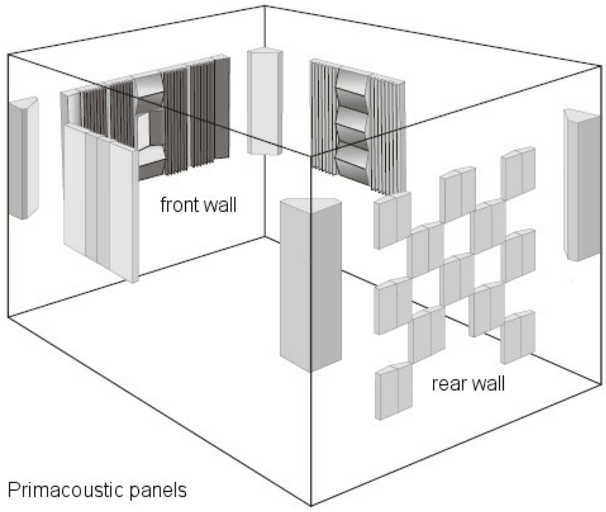

Figure 5. *Absorption to cut first order reflections.*

Absorption over the rest of the room surfaces is less important, as later reflections cause fewer problems. The resulting mixes will be more consistent when heard in other environments, and attention given to moving a sound spatially and generating reverberation will be more successful, creating an acoustic space in which the composition takes place.

Acoustic Identity

It is the experience of the author that many electro-acoustic compositions suffer greatly from a lack of a cohesive acoustic space which makes individual parts difficult to identify and follow. Cursory attention appears to have been paid to introducing some reverberation to different sounds, but there is a lack of a cohesive space blending together components in a manner which would, in the opinion of the author, significantly enhance the listening experience. Another complicating factor arises from the very different outcomes for listening to electro-acoustic music, which include home loudspeaker listening, headphones, performance venues of different sizes and installation environments. Each listening environment will introduce its own acoustic spatial properties, ranging from no influence inside headphones, to significant reflections in a large performance space, to noisy outdoor installations and small, bright lounge rooms and vehicles.

A further complication is the size and quality of the loudspeakers used and their arrangement in the listening environment. Ideally, a composer will know in advance which environment they are composing for, and can modify the piece appropriately. Where an electro-acoustic composition is intended for CD release and personal listening, is it possible to embed an acoustic space in the recording such that the space will be audible in most listening environments?

Imagine a Space!

In an electro-acoustic composition, it may assist listening if the composer creates a common acoustic space in which the sounds occur. This would be a virtual acoustic space conceptually similar to the performance venue for purely acoustic music. Research has proven that early reflections are mostly responsible for a natural sounding room impression and the perception of location and distance. Therefore, it becomes important to control the amplitude, spectrum, direction and arrival time for early reflections to create a virtual acoustic space. Most recent electronic reverberation devices, particularly software reverb plug-ins, allow precise control of these parameters for early reflections separately from late reverberation. Many devices describe these parameters in relationship to real rooms, in terms including room size, shape and surface materials, and allow fine control over parameters.

It becomes important to imagine a space suitable for the composition and to define it in these room characteristics. The density of early reflections affects the perception of the space, with many devices producing twenty to thirty early reflections within the window between 20ms and 80ms being considered, with a higher density creating a more accurate perception of a particular defined space. However, for clarity in the resulting sound, the total loudness of all early reflections should be between -4db and -6dB below the loudness of the direct sound, according to Griesinger [10].

Impulse Response Sampling

There are many reverberation software plug-ins now available which use impulse responses recorded in real acoustic spaces to create virtual spaces for new sounds, for example the Waves Convolution Reverb IR-1, [15]. Using convolution, the direct sound is virtually placed in the original space, taking on the early reflection and late reverberation characteristics of that space. Some of these devices also allow manipulation of each part separately, so that the early reflection patterns can be altered to suit a particular composition with late reverberation adjusted independently.

Impulse response reverberation provides high density reflections measured in real spaces, with independent manipulation of parameters, but comes at the cost of intensive computing power to perform the convolutions. One potential disadvantage is the number of places within the space at which the acoustics were sampled, and how separate samples are combined in the plug-in, as there are great variations throughout the space and a requirement for different impulse responses when creating multi-channel recordings.

Decorrelated Reverberation

As we move between listening positions in an acoustic space, the patterns of early reflections and late reverberation change in amplitude, spectrum and time, and we can measure the degree of correlation or similarity between these patterns. In the critically acclaimed performance venues there is a very great difference in correlation between listening positions, that is they are highly decorrelated, particularly beyond the critical distance. When we create an acoustic space for a composition, we should therefore use highly decorrelated reverberation between different loudspeakers to produce the greatest sense of acoustic space.

The reverberation produced by an impulse response plug-in is sometimes created from a limited number of sampled positions, which would potentially increase correlation between outputs, particularly at low frequencies. To overcome this limitation, several instances of the plug-in would be used, each delivering a mono output to one loudspeaker. Using four instances, very high decorrelation would be achieved between the loudspeakers of a surround sound composition, with a corresponding improvement in the quality of the acoustic space created. Decorrelation of the early reflection patterns will also improve the separation between channels and the accuracy of the room impressions created.

The Direction of Reflections

The direction of the early reflections is also important in creating a high quality room impression. When we are close to a real sound source in a space, the direction of the early reflections will be very wide, and Beranek considered that the most important lateral reflections occur between 35°-75° from the front centre. It is logical to suggest that reflections coming from the same direction as the direct sound will be inaudible as they are partially masked by the direct sound. This is particularly the case with stereo recordings, where it is not possible to spatially separate lateral reflections from the stereo positions of direct sounds, thereby reducing the perception of space or depth in the recording. It has also been shown, [7] and [10], that reverberation from the front is not perceived as being spacious or enveloping, which reinforces the advantages of surround recording and playback in the improvement of spatial impression and envelopment.

Therefore, when creating room impression electronically, it is important to spread the early reflections as widely as possible. If, for example, the direct sound is coming from the front right loudspeaker in a surround playback system, then early reflections should be spread between the front left loudspeaker and the right rear loudspeaker, either side of the direct sound. To further enhance the acoustic space, late reverberation would mainly come from the left rear loudspeaker, opposite the direct sound, to spread the sound further around the listening position, see Figure 6. Ideally all these different reflections should be decorrelated to produce the greatest depth of spatial impression. The use of multiple reverberation generators that are highly decorrelated but with matched room parameters, would result in the most natural sounding room impression and the largest sweet spot.

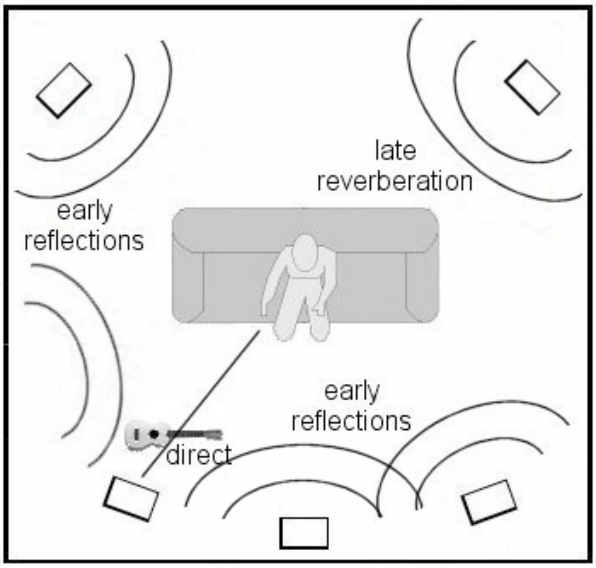

Figure 6. Spatial impression from early reflections and envelopment using late reverberation.

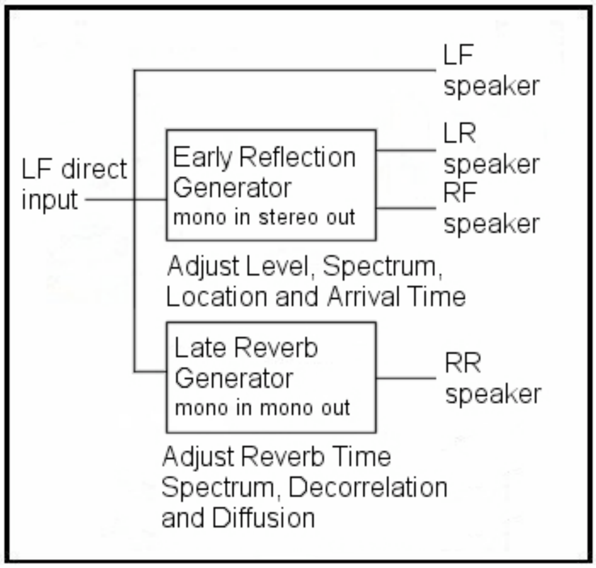

Figure 6. Software implementation for spatial impression and envelopment, repeated for each direct channel.

Software Implementation

To implement this reverberation generation for a surround sound composition, multiple instances of a reverb plug-in would be used with the following setting. Four instances of a decorrelated stereo early reflection generator would be set with a mono input from each of the four main channels and the outputs routed to adjacent channels. For a direct sound in the left front, the ERs generated would come from front right and left rear, and a direct sound in left rear would have ERs in the left front and right rear channels. Note that a direct sound in the right rear channel would have ERs in the right front and left rear channels, identical to the left front position. While it may be possible to use one instance of the ER generator for both sources, separate generators would increase decorrelation, improve crosstalk between channels and also reduce the number of sounds through each generator, which would improve clarity.

To generate late reverberation, four instances of a mono reverberation generator would be used, each driven from one loudspeaker channel and output to the opposite loudspeaker. The use of four mono channels would increase decorrelation and improve clarity. The settings for each instance of ER generator and late reverberation generator would be copied, with minor variations introduced as necessary to maintain consistency but increase decorrelation and improve the quality of the acoustic space created.

Surround with Height

In a previous paper by the author, [2], height has been introduced to a surround playback system using two loudspeakers mounted on the frontal plane, 60° up from the horizontal plane on either side, shown in figure 7. A software implementation of the acoustic space creator described above would use two instances of ERs generation, one for each loudspeaker, and similarly two instances of late reverberation generation. Parameter settings would be copied from the horizontal and slightly varied to improve decorrelation and separation. In practice, the author has found that less late reverberation is required from the elevated positions, while the best settings for ERs have a slightly longer time interval, with a later arrival time creating the impression of clearly perceived height.

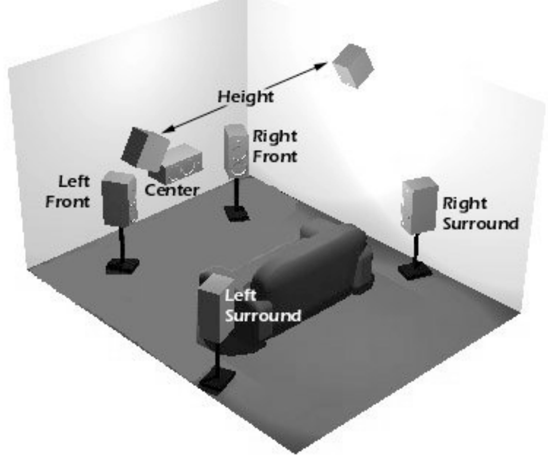

Figure 7: Surround with height: 60 degrees up, 90 degrees from the front.

Reverberation Super-imposition

An important and wonderful characteristic of sound is the audibility of multiple acoustic spaces simultaneously. It is possible to clearly hear the acoustic space around one sound event embedded within the acoustic space of another sound event. We could create a large acoustic space for several sounds in a composition, with a clear room impression generated by early reflections and a large slowly decaying late reverberation tail, and then superimpose another sound closer to us by using shorter pre-delay, tighter early reflections and quick late reverberation. In this way, it is easy to generate greater audible separation between the sounds.

This technique has been exploited by popular music recordings for many decades and has become a distinctive part of its sound, particularly with the close microphone techniques employed in recording studios, where there is little original acoustic space captured in the recording. The final mixing process will employ multiple reverberation devices, each with different parameter setting and used exclusively on only one instrument or voice. Separate devices improve the clarity of the reverberation with decorrelated reflections, individual room impression and tailored late reverberation tails.

Where a recording studio has real acoustic spaces with characteristics suitable and desired by a producer or artist, the use of multi-channel recording techniques allows solo recordings of different instruments or voices, which will improve clarity. It is therefore straightforward to consider creating several different acoustic spaces within a composition, each with a single or group of sounds embedded within it, where the unity of the space is well defined and the sound events within each space blend and cohere into a clearly audible cluster. Using multiple instances of software reverberation devices, each constructed in the way described previously with separate instances for each channel of early reflections and late reverberation, multiple acoustic spaces could be created simultaneously, allowing great freedom in the placement and grouping of individual sound events.

Conclusion

Human perception of the acoustic environment is sophisticated and detailed, though largely subconscious. Until listeners are alerted to 'pay attention' to a particular sound or group of sounds, the three-dimensional context is perceived, processed and incorporated without undue awareness. Most listeners adapt to room acoustics and ignore what acousticians might consider to be audible deficiencies, instead extracting the aural information they desire. Composers working with electronic reproduction need to become familiar with the physical and psycho-acoustic characteristics of perception and acoustic space, so they may use these qualities to enhance their compositions.

The ability to create different acoustic spaces in a recording requires the simulation and manipulation of acoustic reflections to mimic spatial impression and aural envelopment. Spatial impression relies on the patterns of early reflections and the variations in loudness, spectrum, location and arrival time. Aural envelopment relies on late arriving reflections grouped together as late reverberation, with variable qualities of reverb decay time, diffusion, decorrelation and spectrum. Careful manipulation of these parameters can create an infinite variety of natural and unnatural acoustic spaces, from defined rooms to cavernous halls, and can be matched to any style of composition and format of reproduction. Software tools available now allow infinite control of all of these parameters, and often include the stored responses from real spaces.

The final stage in the realization of a composition, where it is mixed to a recording for distribution and reproduction, must incorporate an understanding of acoustic space. The studio environment for mixing the recording will influence the decisions made during mixing, and the acoustics must be tightly controlled. The listening environment will also influence the perception of the reproduction, but is generally benign as listeners quickly ignore acoustic deficiencies. All recordings require careful control of acoustic space in the final mix to enhance the clarity, depth, spatial impression and envelopment of the recording. Therefore the mix must begin with 'imagine a space!'

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