Experiencing the Aural Environment of Rooms

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Electronically created or "virtual" sound fields are generated and presented with an impulse response and a visual image of specific acoustic environments. A variety of different acoustical environments including acoustical defects are demonstrated with both a speaking person and musical instruments as the sound source. This demonstration is designed to convey a qualitative understanding of acoustical events (such as reverberation), and an understanding of how these events are described through the impulse response.

Virtual sound fields are created using commercially available digital signal processing equipment. An anechoic or "dry" recording that contains no reverberation or room effects is modified by electronically adding this information to produce a stereo (binaural) signal that would be similar to one perceived by a listener in a room. The impulse response is used as a means of graphically depicting the specific

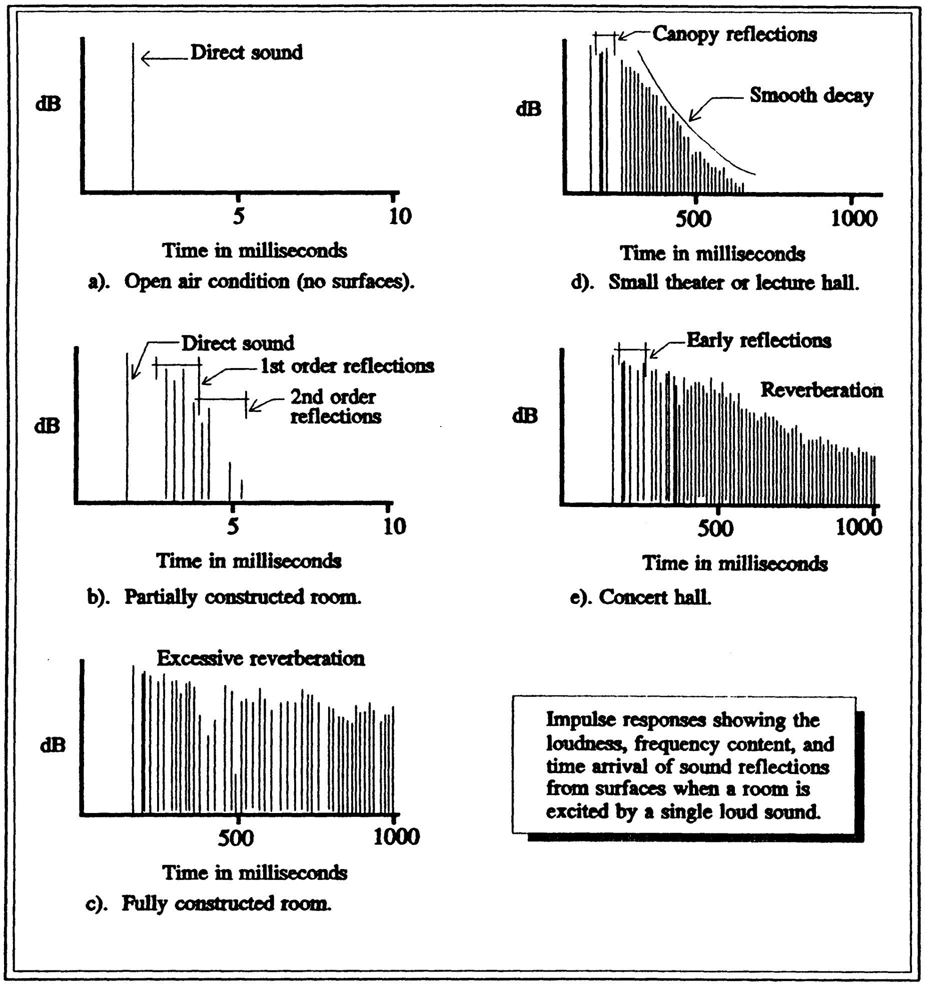


Figure 1. Example impulse responses depicting acoustical events (Siebein et al., 93).

acoustical qualities of the particular sound field that is being modeled. The impulse response can help provide a conceptual understanding of the links between perceived acoustical qualities and the architectural features of rooms. The impulse response is used extensively to characterize sound fields in both computer models, scale models, and full size rooms. Once the impulse response has been generated, the information can then be translated in real time into a virtual sound field. This makes it possible to actually hear how architectural changes to a computer model of a room or concert hall might be perceived at a specific location in the room. The focus of the following demonstration, is to aurally demonstrate different acoustical environments and show how they are characterized by the impulse response.

The impulse response represents the pulsing of a room by a single, loud sound such as a gunshot. Each syllable of spoken words and each note played by musical instruments excite the room in a similar way. The loudness, frequency content, time of arrival, the direction of the direct sound and all of the reflected sounds are included in this measurement. The impulse response will vary with each seat in a room. It represents the unique signature of sound that arrives from a given source to a specific listener. The contribution of the direct sound and reflections from each of the walls, the ceiling, and other architectural elements is also included. A number of objective indices of acoustic qualities can be calculated from the impulse response. In a large room, the impulse response will vary significantly from location to location just as the perceived acoustic qualities do. Additionally, as architectural characteristics of a room are altered so is the impulse response. The impulse response can be used as a basis for suggesting possible architectural approaches to the design of a room or modifications that can be made to an existing room.

Figure 1 shows how each of the surfaces of a room contribute to the impulse response. In part a. a free field or open air situation is shown. The single "spike" is shown as decibels, or a log $(\text{pressure})^2$ format because this is the way our ears respond to sound. There is only a direct sound path from a person speaking to a listener. The loudness or amplitude of the sound decreases as the speaker and listener move farther away from each other. It also takes time for the sound to reach the listener. Therefore the arrival of the sound at the listener's ears occurs somewhat after it leaves the lips of the speaker.

In **b**. a rear wall, one side wall, and a floor have been added. Now several reflections arrive at the listeners location in addition to the direct sound. First order reflections arrive directly after they strike one of the surfaces. Second order reflections arrive after they strike two surfaces in succession, etc. The loudness of each subsequent reflection diminishes because it is travelling a longer path and is geometrically spreading. Some energy is also lost during the reflecting process as the sound interacts with the surface. The longer the path length, the greater the time interval before a subsequent reflection arrives after the direct sound.

In **c**. a complete rectangular room with four walls, floor, and ceiling has been added. This is a four wall racquetball court or a gymnasium. The first order reflections are clearly shown immediately after the direct sound. Lower level reflections persist for quite some time after the direct sound. This is the process of reverberation.

In **d**. the impulse response of a theater is shown. Several strong early reflections from a suspended ceiling canopy arrive shortly after the direct sound to increase the loudness of the sound. The reverberant energy dies away smoothly enhancing the qualities of the sound in contrast to the excessively loud, harsh reverberant energy shown in c.

In **e**. the impulse response of a concert hall is shown. Strong early reflections are followed by a sustained reverberant sound field that decays smoothly but much less quickly than the theater shown above. The lower level reflections that persist after the direct sound indicate a diffuse sound field with surfaces that uniformly scatter the sound in space and time.

The use of digital audio equipment allows one to aurally simulate the sound fields that are described by the impulse response. Changes in loudness, direction and number of early reflections as well as subsequent reverberation can be electronically controlled thus simulating the aural experience of a room environment.

The equipment includes a compact diskette player, digital audio tape (DAT) player/recorder, four -two channel digital delay/reverberation units, and a mixing console. The specific equipment will be discuissed in detail below. These items are extensively used in the music recording industry and are commercially available at a relatively low cost. Figure 2 is a diagram showing the configuration of the equipment used to generate the virtual sound fields.

The source for the virtual sound field can vary greatly, a human speaker, an individual instrument, or an entire orchestra may be used as the sound source. The source is recorded in an anechoic environment. The anechoic environment does not add any sound reflections or reverberation to the source material. This is called a "dry" recording. The source recording for the aural demonstration was produced by the Yamaha corporation and is available on compact disc.

Using the mixing console, the dry source is fed to one of the digital delay/reverberation units. There it is delayed in time or reverberation is added and it is subsequently returned to the mixing console. It is then appropriately blended with the original dry source or "direct sound". Additionally at the mixing console the incoming delayed or reverberation signals are "panned" (sent to the left or right channel or proportionally to both) to create a stereo signal. This signal is then stored on digital audio tape to maintain the highest fidelity and signal to noise ratio. The aural demonstration was mixed using a Mackie® 24 8 mixing console.

The digital delay/reverberation units used were Lexicon® LXP-5 effects processing modules. These units are internally configured in two sections, one section contains delay algorithms that allow the user to control basic aspects

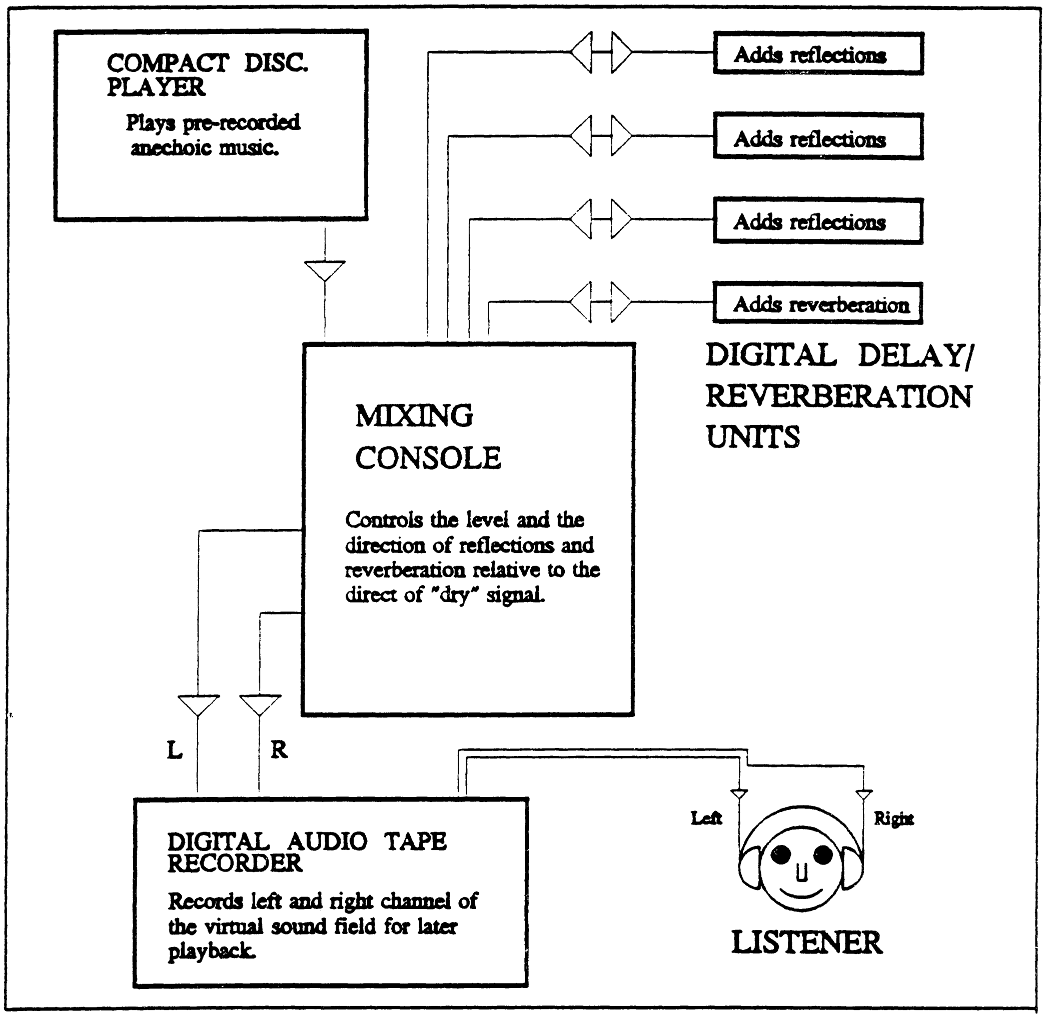


Figure 2. Schematic diagram of equipment to generate virtual sound fields.

of the delayed signal, the other section contains algorithms that control the specific characteristics of the reverberation. the delay time may be adjusted in increments of 20 usec from 0 to 983 ms. Additionally, a feedback loop allows the user to repeat the source signal from one to an infinite number of times at the chosen delay time. The delayed signal or reflection may be filtered with variable high cut (full pass to 320 hz) and low cut (full pass to 1.35 khz). Once the original signal has been delayed in time it is returned to the mixing console to be added to the virtual sound field shortly after the direct or source signal. Additionally, this delayed signal may be sent again, via the mixing console, to another delay or reverberation unit. This delayed signal may also be specifically tailored with a one-third octave graphic equalizer to better represent the way sound would reflect off of a particular architectural surface that might absorb or reflect particular frequencies more than others.

The reverberation section has many parameters in order to better simulate a particular room environment. The 'reverberation time' (RT) may be adjusted from 0.5 seconds to infinity in increments of 0.1 seconds. A room size parameter accounts for the effects of the room volume as it is a function of the reverberant field. A diffusion parameter accounts for the surface articulation in the simulated room. Rooms with more surface articulation will tend to spread the sound more evenly throughout the space. Spaces with minimal surface articulation such as a racquetball court will tend to sound harsh. Furthermore, in larger rooms, air attenuation will absorb energy in the higher frequencies. This is simulated with the bass multiply parameter. This allows the bass frequencies to have a slightly longer reverberation time simulating the effects of air absorption in larger rooms. In small to medium sized rooms with surface materials that absorb bass energy such as gypsum on studs, the bass multiply value could be set to less than 1 thus simulating this effect in the virtual sound field. Another important parameter is the 'room size'. This parameter controls the reverberation in a manner that controls the proportionality of the fine structure of the reverberant field. This parameter is linked to the RT in the reverberation algorithm. Documented information on the reverberation algorithms from the Lexicon corporation were unavailable due to their proprietary nature. However, impulse responses of varied settings of this parameter indicated that it controls the general slope and density of the decay curve.

Once each of the parameters of the system are set, the

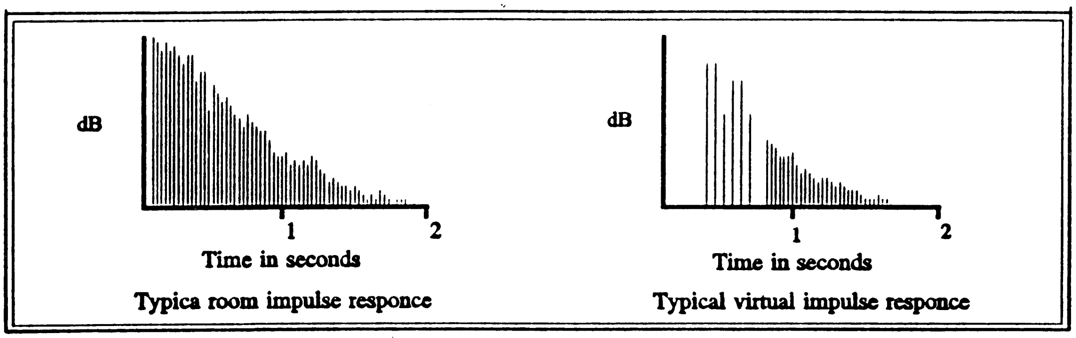
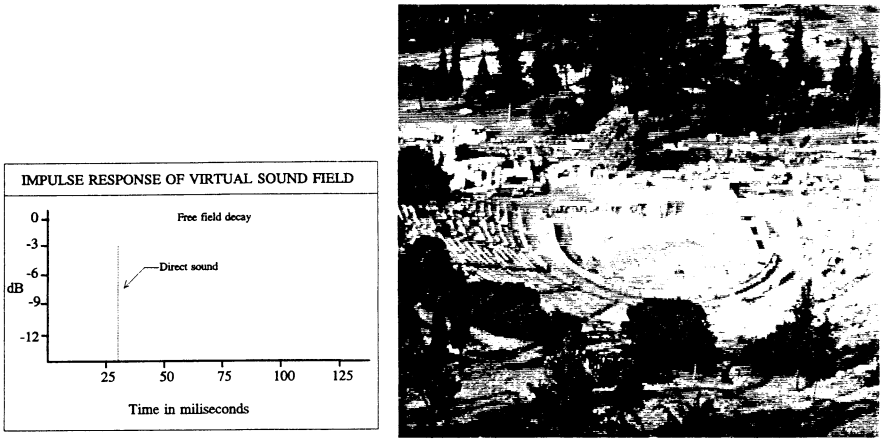


Figure 3. Comparison of room impulse response with virtual sound field impulse response.

DESCRIPTION OF SLIDES

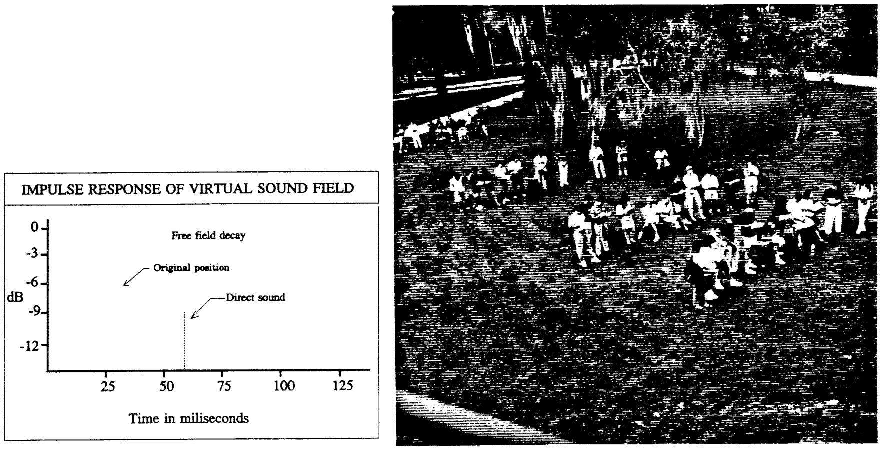
DEPICTION OF SLIDES

1: ***We can simulate being outdoors in an amphitheater. This is essentially a free field condition where one only hears the direct sound that travels form a speaker 10 meters to the listener.***



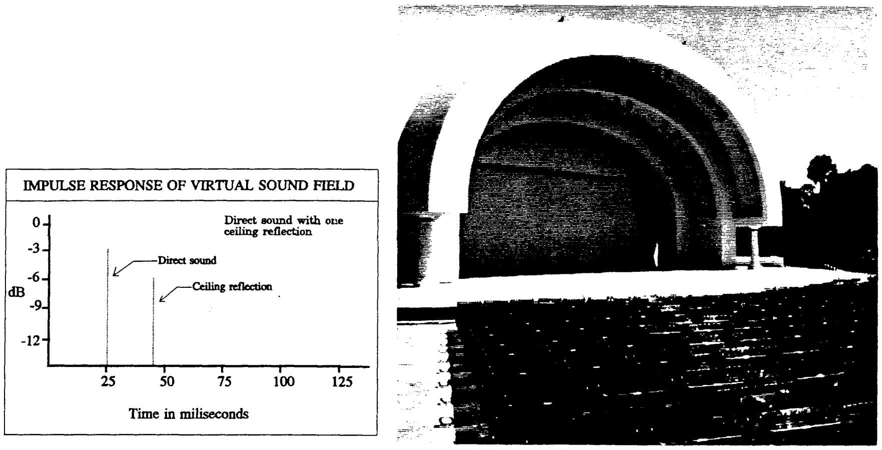
Greek amphitheater. Distance to each audience member is critical as there are no reflecting surfaces.

2: ***If we walk down the aisle of the amphitheater, away from the person who is speaking, the sound level is reduced due to geometric spreading until it is 6 decibels less than the original sound level by the time we have doubled the distance or moved 20 meters away from the sound source. If we continue to walk down the isle to 40 meters, where we double the distance again, the sound will be 12 decibels less than the original signal and is heard as less than half as loud.***



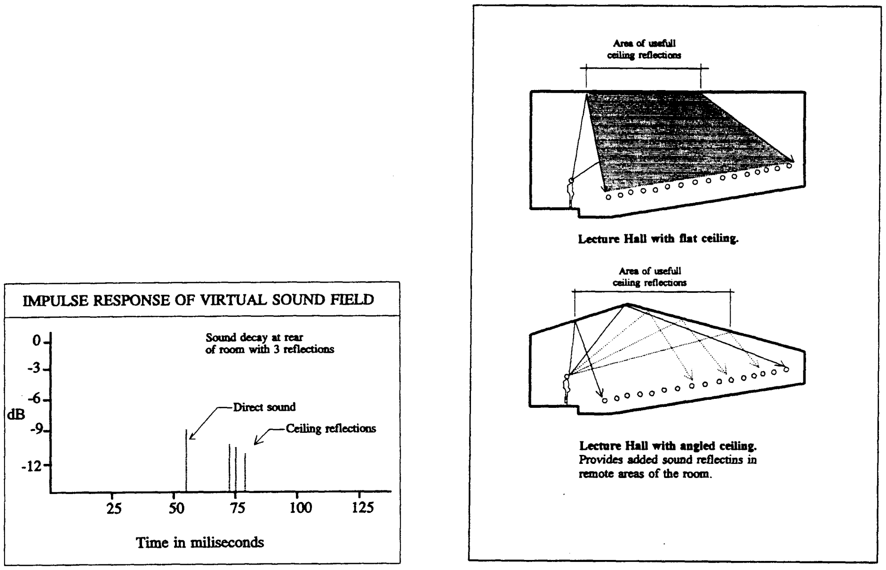
The sound level in the free field decreases by 6 dB as the distance from the source is doubled.

3: ***If a ceiling panel is added to the amphitheater, a reflection will be heard by the listener arriving shortly after the direct sound. This will be perceived as an increase in the overall sound level at the listeners location. However the relative decrease in sound level from the front of the amphitheater to the back will still be heard.***



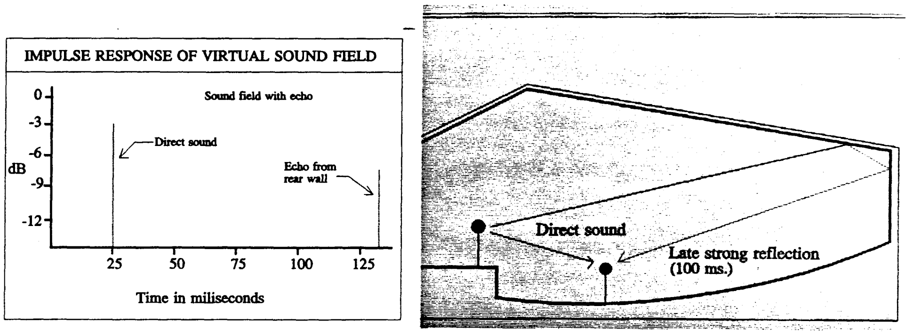
Small amphitheater with overhead reflecting surface.

4: ***If a ceiling is designed to provide three or more reflections arriving shortly after the direct sound in the rear of a room, the sound level will be increased there as well, even though the direct sound has been decreased due to distance. This helps maintain more even sound levels throughout the entire room.***



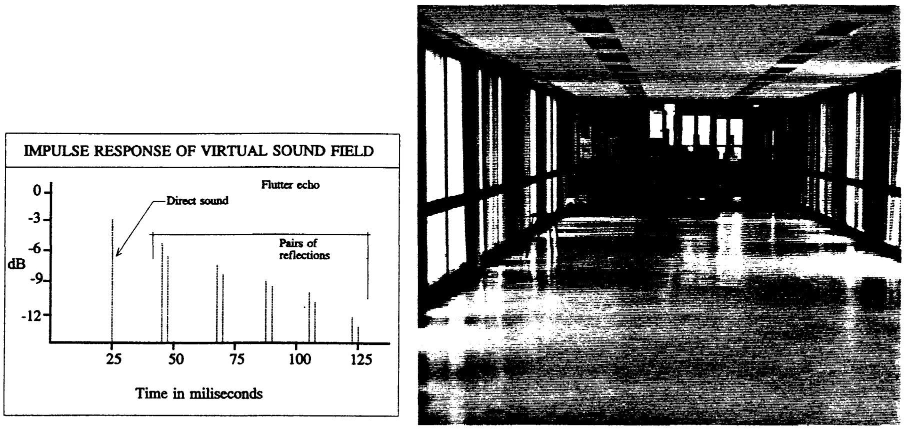
Room section with ray diagram of discrete reflections to the rear of a lecture type room.

5: ***If the rear wall of a large room is made of sound reflective material, such as concrete block or gypsum board, the long delay time between the direct sound (120 ms) and the reflected sound will result in a distinct acoustical event, or an echo to be perceived in the front of the room.***



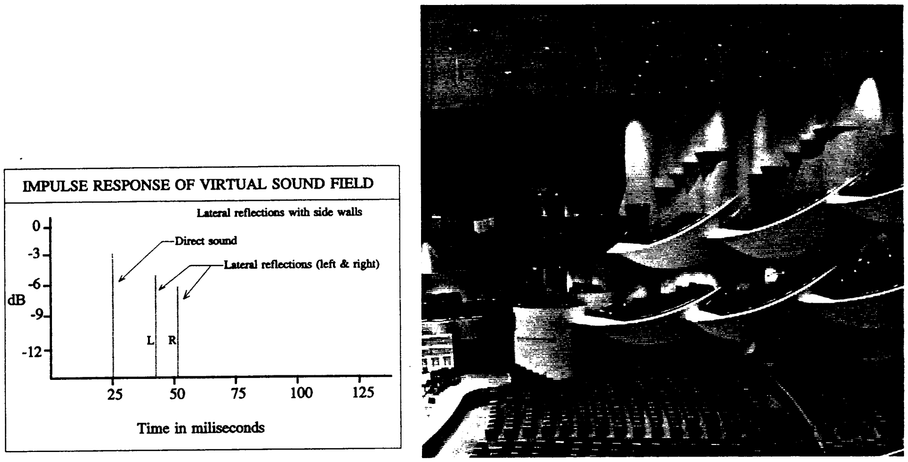
Ray diagram of sound reflecting off the rear wall of a small lecture room.

6: ***If the room has hard parallel side walls a 'slapping', or 'ringing' will occur as the sound bounced back and forth between them. This is called a flutter echo..***



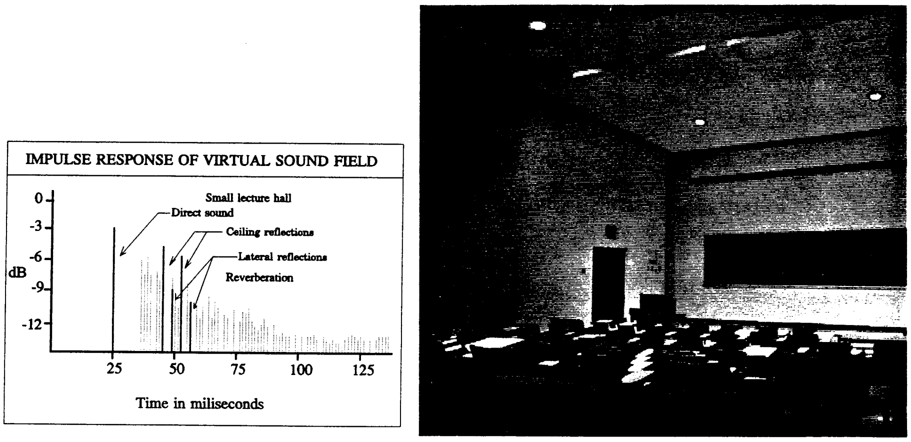
Corridor with parallel glass side walls. Glass is highly reflective in the mid and high frequencies.

7: ***We can add a wall on the left side of the room and direct a reflection from that side to a listener. We can also add a wall on the right side of the room and direct a reflection to the listener, widening the image of the sound. These lateral reflections are thought to enhance the sense of acoustic spaciousness..***



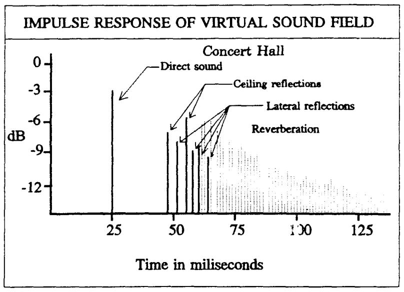
Side walls that provide good reflections to the center of the room yet scatter the reflections to the degree that a flutter echo does not occur.

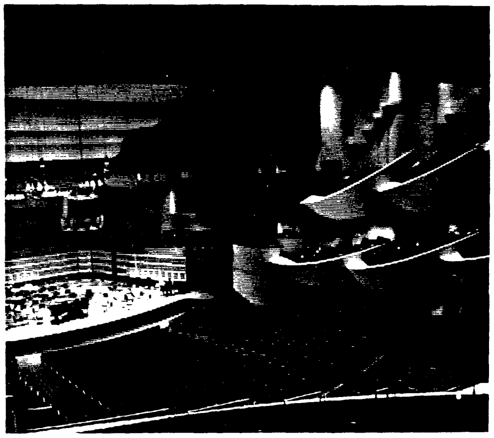
8: ***In a small lecture hall, reflections from both the ceiling and the side walls can be designed to provide relatively uniform sound levels througbout the room. The reverberation time in the room will be a little less than one second.***



Small lecture hall with a reverberation time of approximately 0.8 seconds.

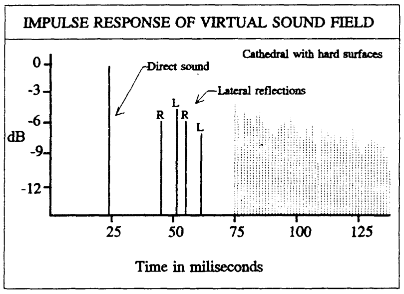
9: ***In a fine concert hall, there will be reflections from an overhead ceiling canopy strong lateral reflections from specially designed side walls and a reverberation time of 2 seconds to enhance the character of music performed in the room.***

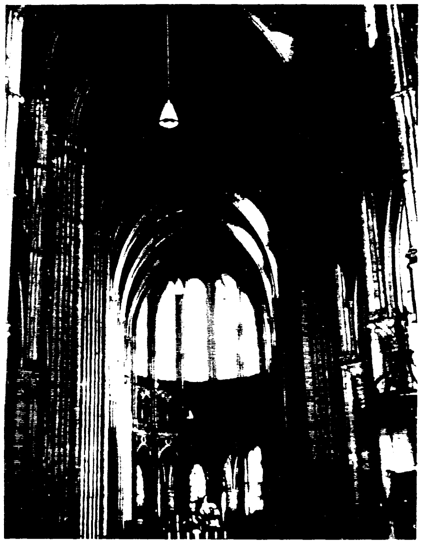




Meyerhoff Concert Hall in Baltimore Maryland.

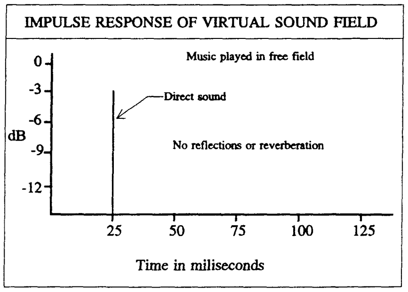
10: ***In a Gothic cathedral, with a large room volume, and all stone and glass surfaces, the sound will persist for over 4 seconds.***

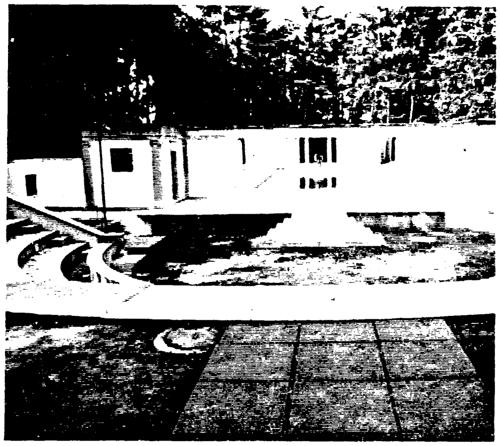




Chartes Cathedral in France.

11: ***The differences in these rooms can also be heard when listening to music in them. The next 4 simulations will use music as the sound source. Each demonstration will be preceded by short clicks recorded with the same impulse response as the music. We will listen to the free field condition first.***





Greek amphitheater with no significant reflecting surfaces.

virtual sound field is recorded on a digital audio tape. They may be played back over a stereo system such as a "boombox", or over headphones. For more detailed research, virtual sound fields may be played over an elaborate array of speakers in an anechoic room. This would require multitrack recording capabilities.

Virtual Sound fields are being used for demonstration, education, and acoustical research. As a research tool they being are used to investigate the relationships between objective acoustical indices and subjective preferences. Additionally, work is being done to aurally model rooms based on impulse responses that have been generated from computer models. Effectively this would allow one to listen to speech or music performed in a room that only exists on a computer screen!

At the present time, the virtual sound fields that are being investigated are relatively simple when compared with sound fields from actual rooms. See figure 3. A typical case would consist of six to eight distinct reflections with subsequent reverberation. However, as the directions of sound arrival, loudness, and frequency balance of the reflections can all be varied electronically relative to the original dry signal in addition to subsequent reverberation (just as in a real room they are varied architecturally), quite significant perceivable differences may be obtained.

The simplification of the sound field for the initial stages of research in this area has psychoacoustic justification. The ear will be unable to discriminate between the large number of reflections that arrive in short time periods in actual rooms. The ear actually integrates the reflections that arrive in time periods that are estimated to vary between 50 ms. and 400 ms. according to psychoacoustic literature. Therefore, using one reflection as representative of the sum of several actual reflections from a similar direction is a reasonable assumption.

Moving reflections directly overhead relative to the direct signal usually results in perceived increases of loudness with no change of direction. Reflections that arrive from the sides usually increase loudness as well, but more importantly, they tend to increase the sense of the apparent aural space. This sense of acoustical spaciousness has been a major area of interest. The subjective sensation has been described as "the difference between feeling 'inside' the music and looking at it as through a window" by the manager of the Concertgebouw Orchestra of Amsterdam. Currently, virtual sound fields are being used to investigate the relationship between laterally reflected sound energy and reverberation as they contribute to a sense of acoustical spaciousness.

Virtual sound fields are a part of the ongoing research in architectural acoustics at the University of Florida, Architectural Acoustics Research Group. Other areas include evaluating existing rooms, experimenting with scale models of rooms, using computers to model room environments, developing computer software to provide objective acoustical measurements of rooms, and through statistical analysis, relating these objective measurements to subjective preferences. Research into these varied areas provides a qualitative basis for evaluating room design approaches from concert halls to classrooms.

The following section is a guide to the slide and tape demonstration. A visual image of a space in which the acoustical environment would be very similar to that on the tape and an impulse response of the sound field will accompany each section of the demonstration. **It is important to note that the acoustical events have been emphasized in order to ensure that they will be perceived when played back in various environments and over differing playback media.** It is essential that the demonstration be played in stereo. The playback environment is a limiting factor and will contribute greatly to the success of the demonstration. A non-reverberant space should yield the best results. Again, the acoustical events have been emphasized to compensate for these issues.