Acoustical Design by Impulse (Response)

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INTRODUCTION

There has been a revolution in the design of concert halls in recent years that has had several major components. First has been a rigorous examination of the renowned "shoe box" concert halls of the late nineteenth and early twentieth centuries such as the Grosser Musikvereinsaal in Vienna, the Concertgebouw in Amsterdam and Symphony Hall in Boston (Johnson, 1990). A more complete understanding of the acoustical qualities of these halls has been undertaken using a variety of techniques developed in allied disciplines. These studies have identified the interactions among the architectural design features and acoustical qualities of the rooms (Siebein, 1994; Chiang, 1994; Beranek, 1996). The techniques used in the studies are listed below.

1. impulse response testing and digital signal processing from electrical engineering
2. laboratory studies of sound quality by human listeners from psychology and neuroscience
3. advanced quantitative tests to determine primary perceptual factors, preference spaces and correlated architectural features of rooms from statistics
4. three dimensional computer and physical modeling of sound propagation in complex spaces from computer science and physics
5. qualitative evaluations of many performances in many rooms by researchers, consultants and musicians
6. deliberate experimentation by consultants and architects to test emerging theories in a series of actual buildings over a thirty year period to evaluate the consequences of this work in holistic architectural settings
7. advancements in virtual acoustics, audio recording, playback and control from digital signal processing and virtual reality.

The combining of these techniques in a hybrid design and research method has resulted in the development of new theories of concert hall design that have been centered on the development of impulse response test techniques[1]. This method which moves between the drawing board, field studies in real rooms and the laboratory has provided a model that recent researchers and consultants have embraced. This method that links laboratory research with the design of concert rooms with the qualitative evaluation of musical performances provides a model for how science in architecture could be conducted to give it cultural and personal meaning. Furthermore, it provides the rationale to suggest that the methods of research used in this emerging science of architectural acoustics can serve as a model for architectural research as a whole.

THE IMPULSE RESPONSE

The impulse response is a physical measurement of the response of a room to a single, loud sound. The direct sound and all of the subsequent reflections from the room surfaces are recorded. This is intended to represent the effects of sound reflections from the room on a single musical note or a single syllable of speech. The loudness, frequency content, arrival time and direction of the sound reflections can be identified from an impulse response[2]. Please refer to figure 1. There are three primary components to the impulse response recorded at a seating location in a room.

1. The direct sound is the sound wave that travels directly from the source to the listener without striking any of the surfaces of the room. It is the first sound wave that arrives at a listener's location. It contributes to sensations of loudness, clarity and localization.
2. The early sound reflections are sound waves that strike one of the room surfaces and are reflected to the listener's location. Reflections that arrive within short time intervals after the direct sound (less than 80 milliseconds for music) are usually combined with the direct sound by the ear. These reflections add to the direct sound increasing its apparent loudness. If the reflections arrive within 40 milliseconds or less after the direct sound, they will also contribute to a sense of acoustic clarity and intimacy. Early reflections that arrive from the sides of the listener's head also contribute to sensations of envelopment and widening of the acoustic image of the sound source.

3. The reverberant sound field consists of sound waves that have been reflected from multiple surfaces before they arrive at the listener's ears. They travel long distances between reflections and are therefore are progressively reduced in loudness from the direct sound and early reflections. The reverberant sound field may persist for 2 seconds or longer in concert halls. It contributes to sensations of reverberance. If the reverberant sounds arrive from many directions and are not exactly the same at the two ears of people listening, it will also increase the sensation of acoustic spaciousness in the room. If the reverberant sound field has strong low frequency or bass components, it will increase the sense of warmth in the room. If it has strong higher frequency or treble components, it will contribute to the perception of brilliance.

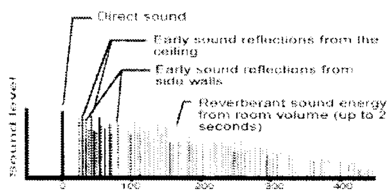

Figure 1. Diagram of a typical impulse response.

The impulse response is unique to each seating location in a large room because it is derived from the specific paths that the direct sound and all the subsequent sound reflections take as they move from the each source to each receiver. Within large rooms, significant variations in impulse responses have been found. These differences among impulse responses in a room provide physical evidence that helps to explain why certain seats are perceived as being better than others (Beranek, 1996; Kuttruff, 1991; Siebein, 1994).

APPLICATIONS OF THE IMPULSE RESPONSE

Impulse response tests have been the catalyst that has unified the knowledge gained from the disparate fields discussed above into a unified set of design principles that can be analyzed and applied in practice. Impulse responses have been recorded in many concert halls and theaters around the world (Barron, 1993; Beranek, 1996; Carvalho, 1994; Chiang, 1994). This catalog of impulse responses for specific seats in specific halls provides a data base for architects and consultants to use in the design and evaluation of rooms.

There are a number of acoustical measures that can be calculated from the impulse responses. These include reverberation time, early reverberation time, early to late temporal energy ratios such as the clarity index or C80, loudness or strength, lateral fraction, interaural cross correlations and support (Ando, 1985; Barron, 1993; Beranek, 1996; Schroeder, 1965; Siebein and Kinzey, 1998).

Listening in Rooms

There have been several major studies where questionnaires have been given to people to evaluate the acoustical qualities of rooms during live or recorded performances. The scores for these qualities have been statistically related to the architectural features of the rooms and with acoustical measures (derived from impulse responses)made in the rooms. These studies have identified significant architectural features that contribute to one or more of the acoustical qualities as defined by people listening in the rooms (Barron, 1993; Beranek, 1996; Cremer, 1982; Gade, 1989; Hawkes and Douglas, 1971; Schroeder, et al, 1974).

Many acoustical consultants and researchers spend a lot of time listening in as many different rooms as possible to performances by as many different groups as possible. This allows them to develop a personal, experiential catalog of acoustic impressions and architectural environments that can be related in a cause and effect manner. They will also interview musicians, music directors and critics to gain critical evaluations of many rooms.

Case studies of impulse response measurements made in a number of concert halls have revealed many subtle relations among the architectural features of rooms, the acoustical qualities of the rooms identified by people listening in the rooms and the sound reflections that create these sensations. This has enabled theories that relate the sense of acoustical intimacy for example to the time interval between the direct sound and the first reflection from the room surfaces. In many instances, the impulse response study was conducted after the qualities had been identified by a researcher or consultant through listening in rooms. Table 1 presents a summary of current hypotheses linking acoustical qualities with physical acoustic phenomena, architectural design features of rooms and acoustical measures that have resulted from this research effort (Beranek, 1996; Siebein and Kinzey, 1998).

ACOUSTICAL MODELING

Modeling of sound propagation in computer models of rooms has advanced to the point where the paths of individual sound reflections can be traced through a room to multiple listening locations. The computer models can produce impulse responses from a number of sound sources to locations selected throughout the room in relatively short periods of time. One can chose any of the individual sound reflections in an impulse response and see which architectural surfaces it has struck on its path from the source to the listener. Many of the acoustical measurements derived from impulse responses in actual rooms can also be calculated by the acoustical modeling software packages. Several efficient algorithms have been developed to approximate sound diffusion in recent years increasing the accuracy of the computer models greatly.

Similar analysis can also be undertaken using physical scale models of rooms. Spark impulses or pseudo random noise signals propagated through small loudspeakers are used as source signals and played into scale models of rooms.

Table 1. Summary of current hypotheses linking acoustical qualities with physical acoustic phenomena, architectural design features of rooms and acoustical measures that have resulted from this hybrid research and design effort (Siebein and Kinzey, 1998).

Acoustic Quality	Architectural Feature that Creates Acoustic Quality	Physical Acoustic Event that Creates Acoustic Quality	Acoustic Measurement that Quantifies Acoustic Quality
Loudness	Room size (1000-2000 seats) Proximity to source Acoustic sight lines	Distance from the source Sound reflections from the ceiling and walls arriving shortly after the direct sound	Loudness (L) or Relative strength (G)
Relative Quiet	Walls, roof and doors with adequate sound transmission loss (STC) ratings to reduce intruding sound levels Quiet HVAC systems	Sound pressure level of intruding sounds	Noise Criterion (NC) Room Criterion (RC) Balanced Noise Criterion (NCB) <20
Reverberance	Large room volume Sound reflecting materials, Shoebox shape, Acoustical banners Reverberation chambers	Prolonging of sound in the room	Reverberation time (RT) (2.0sec) Early Decay Time (EDT)
Spaciousness	Surface texture and sound diffusing materials Large room volume	Late sound energy arriving from the sides (After 80-100 msec)	Interaural cross correlation IACC (<0.50) Surface Diffusivity Index (SDI)
Envelopment and source width	Narrow rooms from 70-80 ft across multiple tiers of narrow balconies	Early sound reflections arriving at the listener form the side (up to 80 msec after the direct sound)	Lateral energy fraction (LEF) LF<0.40
Clarity	Sound Reflecting Ceiling Ceiling Canopy Parterre Walls	Sound reflections that arrive shortly after the direct sound	Clarity index (C80) Early to late energy ratio
Intimacy	Orchestra in same room volume as audience Reflecting surfaces to create reflections with short delay times (after the direct sound)	Arrival of the first sound reflection from a building surface shortly after the direct sound	Initial time delay gap (ITD) (<20MSEC)
Warmth	Heavy massive building materials with large enough area to reflect low frequency sound	Persistence of sound at low frequencies or Extended low frequency reverberation strength of low frequency sounds	Bass ratio (>1.0) Strength of bass sounds (Glow)
Brilliance	Heavy massive building materials	Persistence of sound at high frequencies or extended high frequency reverberation	Treble ratio (approaching 1.0)
Balance	Enclosure designed to uniformly distribute reflected sounds in the room	Balance in loudness between orchestra and soloist Balance in timbre among frequencies of sound	
Localization of sound	Clear sight and sound line between listener and source	Strength and direction of direct sound relative to subsequent reflections	Early loudness level (G10)
Ensemble	Overhead and side wall sound reflecting surfaces at the performance area	Sound reflections that allow the musicians across stage to be heard	Support (ST100 and ST200)
Blend	Design of orchestral enclosure	Sound builds up in the performance area and blends before it is "sent" to the audience area	Inversion Index (I.I.) Ratio of EDT stage/EDT audience

Impulse responses can be obtained from these sources at a variety of locations in a scale model of a room being designed. Changes can be easily made to the model allowing several alternative design schemes to be explored. An iterative series of impulse responses can be obtained that allows one to understand the acoustic effects of their design decisions while the building is still in the early stages of design.

It is also possible to mix or convolve music or speech recorded in an anechoic environment with impulse responses obtained from scale models or computer models of rooms that are being designed resulting in an aural simulation of the acoustical qualities. One can then listen to the aural simulation of music or speech as it would sound in the room that is being designed. One can compare the aural qualities of scheme 1 with scheme 2. For example, one could compare the aural effects of changing the angle of a ceiling panel or widening the room somewhat (Beranek, 1996; Siebein and Kinzey, 1998).

LABORATORY STUDIES OF SOUND QUALITY

Once one has developed a holistic understanding of the acoustical qualities of rooms derived from listening and measurements in situ, further study can proceed by isolating variables in laboratory tests. Sound reflections from architectural surfaces that contribute to the impulse response can be isolated and studied effectively in physical or computer models of rooms. How individual sound reflections contribute to impressions of acoustical quality can also be studied in laboratory situations.

Recordings of anechoic music that have been mixed or convolved with the impulse response of a specific seat in a hall can be altered and played back to listeners through headphones or loudspeakers in an acoustical listening room so they can qualitatively evaluate the simulated sounds. Similarly, using digital signal processing equipment, reverberation and individual reflections can be added to music or speech. The reflections can be programmed to come from specific directions, at specific loudness levels and at particular time intervals after the direct sound to simulate the effects of reflections from a ceiling or wall in a room. The arrival time, frequency content, loudness and direction of the reflections can be changed to simulate a second location for a wall or an alternative material selection. The second sound can be played to listeners so they can give an appraisal of the relative qualities of each condition (Ando, 1985; Beranek, 1996; Blauert and Lindeman, 1986; Cremer, 1982; Gold, 1994; Haas, 1972; Soulodre and Bradley, 1994).

This ability to isolate specific sound reflections in a complex impulse response has been a major contribution to the understanding of room acoustics. One can identify which reflections are responsible for specific sound qualities. One can also identify which architectural features of the room have produced the reflections. This allows one to design the aural environment of rooms and evaluate the aural consequences of the design before the room is built in a manner that is similar to the way in which architects have traditionally designed the visual environment of rooms.

CONCLUSIONS

The design of performance spaces is emerging as an exciting acoustical and architectural building type. The acoustical qualities of these rooms have been developed through careful studies of historic precedents, modeling, simulating, listening and designing in a hybrid design method. The impulse response has been the catalyst that has fused current knowledge in music, electrical engineering, computer simulation, virtual reality, architecture, acoustics and statistics in a highly successful approach to design rooted in knowledge that is emerging from all of these constituent disciplines (Beranek, 1996; Johnson, 1990; Siebein and Kinzey, 1998).

The work described above represents a unique combination of basic science, advanced technology and artistic expression of the union of music, acoustics and architecture. Furthermore, this method also forms a model for a truly architectural research method that can be applied to other sub-fields within the totality of architecture. It explores the fundamental relationships among people, technology and environment in sensory and spatial terms. It provides advances that are becoming valued contributions to our society and it expresses the highest ideals of the people working in this endeavor.

Once one gains a scientific understanding of the basic phenomena in the field, and forms a sophisticated technology appropriate for the time and place, one can proceed to create beautiful buildings. Buildings that are more finely tuned to the people that use them. Buildings that embody the notion of craft and expression inherent in the concept of techne in their design and their construction.

> "The expression that is the aegis of our profession is to bring forth the true into the beautiful" (McLeary, 1983).

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ENDNOTES

1 The impulse response test method was borrowed from digital signal processing. It is a basic premise of linear systems theory. If a system under test is subjected to an impulse. the response obtained is a result of the properties of the system plus the characteristics of the impulse.

2. Impulse responses were originally recorded from a hand clap. a bursting balloon. a gun shot or an electronic pulse played through a loudspeaker. They were recorded on oscilloscopes and photographed for analysis. Currently sophisticated pseudo random noise signals such as maximum length sequences and complex sine sweeps are programmed in signal processing software in a portable computer. sent through a digital to analog converter. amplified and played through loudspeakers into the room. The pseudo random noise signals are more repeatable than the actual impulsive sources such as the hand clap or gun shot.

3. The lateral fraction is an acoustic measure that relates the amount of sound that is received at a seat from the sides to the total sound energy that arrives at the seat. The lateral fraction has been related to the acoustical quality of envelopment and source width in laboratory studies where simulated sound fields were constructed to isolate the acoustic effects of early lateral sound reflections.

4. Reverberation time is the amount of time it takes for the sound to decay to a level that is 60 dB less than the original level. It is derived from a least squares fit of the reverse integration of the impulse response of a room.

5. The relative strength or relative early loudness are acoustic measures of loudness. Many of the precedent halls have remarkably consistent loudness levels throughout the rooms.

6. The hearing conditions on stage are currently evaluated by an acoustical measure called support. The energy of reflected sounds heard on stage are recorded over short time intervals. The time intervals were chosen based on interviews with musicians regarding stages where adequate support for their listening was provided by the room.

7. The sense of intimacy is related to the initial time delay gap. This is the difference in arrival time between the direct sound and the first reflection from the room surfaces.

8. The bass ratio is an indication of the relative warmth or the support of bass or low frequency sounds in the room. It is a ratio of the reverberation times in the lower frequencies to the reverberation times in the middle frequencies. The bass ratios were usually high in the precedent halls.

The treble ratio is an indication of the relative brilliance or support of higher frequency sounds in the rooms. It is a ratio of the reverberation times in the higher frequencies relative to the reverberation times in the middle frequencies. The treble ratios tended to be fairly high in the precedent rooms as well.

9. The interaural cross correlation or IACC is a physical measure that is intended to indicate the relative dissimilarity of the sounds that arrive at the left and right ears of people. In laboratory studies it has been found that seats in rooms that have low IACC values are generally preferred by listeners. This would mean that people prefer listening to music where the sound that arrives at the left ear is different than the sounds that arrive at the right ear. Most of the precedent halls have relatively low IACC values.