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Metrics

What do you notice about the sound quality when you are listening to a concert in your favorite hall? Is it clear, dry, intimate, warm, fuzzy, brilliant, loud? Acousticians have compiled a list of acoustic qualities that are considered to be most important in concert hall acoustics. The following pages contain information on these subjective qualities, how they are quantified and measured, and how one may design for concert halls that exhibit these qualities.

- Reverberation
- Clarity
- Intimacy
- Warmth and Brilliance
- Loudness
- Spaciousness
- Background Noise

Reverberation

Subjective quality:
The most commonly perceived quality of room acoustics is how sound energy decays in a space, referred to as the room's reverberation. In a large gothic cathedral, the sound takes a long time to die away, sometimes up to 9 seconds! In a small conference room, however, the sound does not linger but decays very rapidly. Longer reverberation generally accentuates music, but can cause speech to be muddled. For concert halls, musicians will often refer to a reverberant space as being very "live". If there is not very much sound reverberation, a hall may be referred to as being "dead".
Listen to different reverberation times.

Objective measure:
Wallace Clement Sabine was the first to quantify this subjective quality in the early 1900s. He developed the quantity Reverberation Time (RT), which is defined as the time it takes for sound energy to decay 60 decibels (dB). One can measure this in an existing room, by measuring the length of time for sound to decay 20 dB (from -5 dB down from the peak to -25 dB down) and multiplying that period by three. Or for prediction, one can use the following equation:

$$RT = \frac{0.16V}{S(\overline{\alpha})}$$

where V is volume in cubic meters, S is total surface area of the room in square meters, and α is the average absorption coefficient in the room.

Calculate a room's reverberation time.

Optimum values:
Optimum reverberation times for concert halls depend on the type of music for which the hall is being designed. Generally, good concert halls have a reverberation time between 1.8 and 2.2 seconds at mid-frequencies.
Click for RT's of famous concert halls.

How to design:
To increase reverberation time, one could increase the volume of the room, or reduce the amount of absorption in the room.

Other notable info:
More recently, acousticians have studied early and late portions of the sound decay separately. The early part of the sound decay seems to determine better how an audience perceives music. An objective measure for this is called the Early Decay Time (EDT). EDT is calculated by measuring the amount of time it takes sound energy to decay the first 10 dB, and multiplying that by six. In concert halls, it is desirable to have a shorter EDT to improve clarity, but a longer RT to provide live-ness to the music.

Clarity

Subjective quality:
Clarity refers to how clear the sound quality is. Can you hear every separate note of a fast-tempo soloist's coda distinctly, or do the notes tend to blur into one another? Some blending is often desired for music, but for speech and opera, greater clarity leads to better speech intelligibility.

Objective measure:
Clarity is produced when a room has a high ratio of early sound energy to later reverberant energy. Early sound energy is that which arrives at the listener within 80 milliseconds of the direct sound from the source to the listener. A popular objective measure for clarity is the Clarity Index, . This is defined as the logarithmic ratio of early sound energy, arriving in the first 80 ms, to late sound energy, arriving after 80 ms:

$$\mathbf{C_{80}} = 10 \log \text{(early sound energy/late sound energy)}$$

The units of $\mathbf{C_{80}}$ are decibels (dB).
Like many of the acoustic qualities discussed on this website, $\mathbf{C_{80}}$ is dependent upon frequency. Therefore, $\mathbf{C_{80}(3)}$ has been developed to give an overall idea of what a room's clarity is. $\mathbf{C_{80}(3)}$ has been defined as the average of $\mathbf{C_{80}}$ values at frequency octave bands centered at 500 Hz, 1000 Hz, and 2000 Hz.
Listen to spaces with different $\mathbf{C_{80}}$'s.

Optimum values:
In general, acceptable values for $\mathbf{C_{80}(3)}$for concert halls are between +1 dB and -4 dB.
Click for $\mathbf{C_{80}(3)}$'s of famous concert halls.

How to design:
To increase clarity, one should increase the amount of early sound energy relative to late sound energy. This could be accomplished by adding absorption in areas farther from the sound source.

Intimacy

Subjective quality:
In concert halls, intimacy refers to the feeling of being close to the source of the music. This impression is usually present in smaller halls, but it is often difficult to achieve in larger spaces. In large halls that have not been designed with intimacy in mind, the audience may feel remote and detached from the performance.

Objective measure:
Intimacy is quantitatively measured by the initial time-delay gap (ITDG). This quantity is given by the time difference between arrival of the direct sound and arrival of the first significant reflection at a certain receiver position. If a space has a relatively short ITDG, it is said to be more intimate; a longer ITDG indicates less intimacy. In smaller halls, enclosing surfaces are closer together, so reflections occur more frequently than in large halls where surfaces are farther apart. Therefore, smaller halls generally have shorter initial time-delay gaps.
Because the initial time delay gap can depend on receiver position, it is standard to measure ITDG at a position roughly in the center of a hall for comparison purposes.
Listen to seats with different ITDG's.

Optimum values:
Appropriate ITDG's depend on the type of music for which a space is being designed. However, in general, concert halls are more successful if they have shorter ITDG's, somewhere between 12 and 25 milliseconds.
Click for ITDG's of famous concert halls.

How to design:
To increase ITDG, one should shorten the distance from the first reflecting surface to the audience area. In larger spaces, this may be accomplished by adding ceiling reflectors or protrusions from the walls.

Warmth and Brilliance

Subjective quality:

Warmth is a term used to describe a cozy smoothness to the music. Its counterpart may be considered to be brilliance, which refers to a bright, clear, ringing sound. Either one of these qualities is desirable in moderation. If a sound field is too warm, the hall can be undesirably “dark.” With too much brilliance, the sound is harsh, brittle, and metallic sounding”.

Objective measure:
Acousticians have determined that balancing warmth and brilliance is achieved by balancing the ratio of low frequency Reverberation Time (RT) to high frequency RT. Thus, the Bass Ratio (BR) has been suggested as an objective measure of warmth:

$$BR = \frac{RT_{125\,Hz} + RT_{250\,Hz}}{RT_{500\,Hz} + RT_{1000\,Hz}}$$

where the numerator is an average of RT’s measured in the 125 Hz and 250 Hz octave bands, and the denominator is an average of RT’s measured in the 500 Hz and 1000 Hz octave bands.
Listen to halls with different Bass Ratios.
Calculate Bass Ratio.

Optimum values:
A bass ratio between 1.1 and 1.25 is desirable in halls with a high RT, and a bass ratio between 1.1 and 1.45 is recommended for any hall with an RT of 1.8 sec or less.
Click for Bass Ratios of famous concert halls.

How to design:
To increase the warmth, one should increase the low frequency RT while maintaining or decreasing mid to high frequency RT. One way to do this is to add materials in the space which absorb energy at high frequencies better than at low frequencies. However, the balance between warmth and brilliance should be kept in mind; excessive high frequency absorption will reduce brilliance unfavorably.
Loudness

Loudness

Subjective quality:
The loudness of sound in a hall is obviously very important: the audience needs to be able to hear the performance without straining. Loudness can affect perception of other acoustic qualities as well, such as intimacy and spatial impression (for example, if the sound is too quiet, we do not feel that the space is intimate).

Objective measure:
Loudness in a concert hall may be objectively measured by the strength factor, G, in decibels. This is the measured sound pressure level at a position in the hall, relative to the sound level of the same source in a free field measured 10 m away:

$$G = SPL_{hall} - SPL_{free,10m}$$

G may be different for each frequency in a given space, so G(mid), which is the average of the measured values of G in the 500 and 1000 octave bands, is most commonly used to describe the loudness of a hall. Substituting the RT equation into this one shows mathematically what we know logically: Loudness is inversely proportional to total surface area and absorption in a space. So in general, the smaller a room is, the louder sound will seem. Also, a room with more absorptive materials (producing a lower RT) will seem quieter than a room with more reflective ones.
Listen to halls with different Loudness.
Calculate Loudness, from RT and V.

Optimum values:
The best concert halls have a strength factor G between 4.0 and 5.5 dB.
Click for G(mid)’s of famous concert halls.

How to design:

Techniques to increase mid-frequency RT, such as reducing absorption in the space, generally help to strengthen G(mid); however, too much reverberation can cause muddled sounds, as discussed in the section on Clarity. An acoustician must balance the needs for strength, reverberation and clarity in a hall.

Side note: The strength of direct sound coming from the sound source will also affect perceived sound loudness. The direct sound level decreases the farther away an audience member is from the source, until you reach the reverberant level of the room. This distance (where the direct sound level equals the reverberant sound level) is called the critical distance, R, and may be calculated from the following formula:

$$R = \sqrt{\frac{Q(S\overline{\alpha})}{16\pi(1-\overline{\alpha})}}$$

where S is total surface area, Q is the directivity factor of your sound source (=1 if source radiates equally in all directions), and α is the average absorption coefficient in the room.

Spaciousness

Subjective quality:
Spaciousness or spatial impression is a term that was introduced in the 1970s to refer to a listener's feeling of being enveloped in the music. Much research on this concept has occurred in the past three decades, and now two aspects of spaciousness have been identified:

Auditory Source Width (ASW)	describes how large and wide the sound source appears to the listener.
Listener Envelopment (LE).	Listener envelopment, meanwhile, addresses how the listener feels surrounded by the music, rather than listening to it as if through a window.

Objective measure:
Early studies on spaciousness determined that lateral reflections, or those coming from the side, play a large role in its perception. The distinction between ASW and LE is dependent on when those lateral reflections arrive.

- Early lateral reflections (within 80 ms of the direct sound) seem to affect ASW,
- Late lateral reflections (after 80 ms of the direct sound) affect LE.

Various objective measures have been suggested for spaciousness, each of which suggests a different mechanism for its perception. Among the first was Lateral Energy Fraction (LF), which is a ratio of sound energy arriving laterally over sound energy arriving from all directions. Interaural Cross-Correlation Coefficient (IACC) was soon introduced; it measures the cross-correlation between the signals that arrive at the two ears of a listener. The more dissimilar the signals, the more spaciousness is perceived. Each of these may be calculated for early reflections or for late reflections, and thus indicate ASW or LE respectively. More recently, a measure known as Late Lateral Level (GLL) has been introduced for listener envelopment. This measure quantifies the strength of laterally arriving sound energy, similar to the strength factor G for loudness. Research is still ongoing about which objective measure gauges spatial impression the best. Listen to different values of LF.

Optimum values:
Higher values of LF and lower values of IACC are said to correlate with greater feelings of spaciousness. LF(E4), the early lateral fraction over four mid-frequency octave bands, is around 0.2 for popular halls. The quantity (1-IACC(E3)), where IACC(E3) is the early IACC over three mid-frequency octave bands, ranges from 0.6 to 0.7 for popular halls.
Click for IACC/LF's of famous concert halls.

How to design:
To increase lateral reflections, add irregularities to the hall: use reflective surfaces, ornate decorations, or sculptures, particularly on the sides of the audience.
Background Noise

Background Noise

Subjective quality:
Background noise may be defined as background sound that is apparent in the room, stemming from many possible sources such as the heating, ventilations, and air-conditioning (HVAC) system, other equipment in the room, exterior sources such as traffic or airplane noise, or neighboring spaces.

Objective measure:
Currently there are two noise criteria that are recommended in ANSI standard S12.2-1995: Balanced Noise Criteria (NCB) and Room Criteria (RC). However, many more have been proposed in recent years, including Room Noise Criteria (RNC) and RC Mark-II. Research is needed to validate these various rating sytems with actual subjective testing data, and to develop criteria which can characterize the effects of discrete tones and time-varying fluctuations.
The calculations of many of the noise criteria methods listed above involve first measuring the sound levels in octave bands across a certain range and comparing them to certain developed curves.
Click to download Excel worksheets for calculating NC and RC: NC-RCworksheet

Optimum values:
Optimum values of background noise for concert hall settings are quite low (NC-20 or lower, RC-20(N) or lower).

How to design:
To meet low noise criteria rating, one should carefully design the HVAC systems: use low air velocities, appropriately NC-rated diffusers, and well-balanced duct designs. Self-generated noise can be a problem in these systems too. To reduce this type of noise, encourage smooth flow throughout the system (with turning vanes and smooth transitions between ducts), and place dampers as upstream as possible from diffusers.