

Chapter 2

Auditorium Acoustics: Terms, Language, and Concepts

There have been primarily three methods for performing subjective studies of the acoustics in concert halls for classical music, each of which has its advantages and disadvantages. One method has been to create a virtual concert hall in a laboratory, where either recordings from a given hall or simulations from room-acoustics software were presented to the listeners. The acoustics could either be simulated with an array of loudspeakers in an anechoic chamber or auralized and presented over headphones. With this method, listeners can quickly rate many halls without having to travel long distances. Some other benefits are that halls can be presented anonymously and blindly so that there is no bias based on a hall's reputation or visual appeal, and the exact same performance of a piece of music can be evaluated in all halls and positions. Despite these advantages, it can be difficult to get truly qualified listeners, such as professional musicians with their busy schedules, to participate in a laboratory experiment. More important, the actual perceived sound in such experiments is very far from the actual listening impressions in the real halls. It is the author's opinion that it is questionable whether the approach has a good enough connection to reality.

In search of a research model that is manageable and practical, decisive information may be lost. Fortunately great care is taken before making recommendations for the building of concert halls based on results originating from this approach. An elaborated test method, used for instance by Lokki and Pätynen, is to place numerous loudspeakers, each with an anechoic recording of a particular instrument in the relevant position on stage in real concert halls. The total "loud-speaker orchestra" is then recorded in different locations among the audiences. Each recording is then later played back over several loudspeakers in a quite anechoic room for test persons to evaluate. This gives quite surprisingly detailed auditory information. Testing isolated acoustical attributes and how they affect humans may be tested in such set-ups. For truly evaluating a hall the method may not prove adequate.

As an alternative, listening tests can be performed in an existing hall where there is a possibility of changing the acoustics. However, the acoustical changes

that have been possible to make have formerly been somewhat limited and typically have not included the low frequencies. The variations have been based on changes of the amount and placement of absorption in the room leading to different reverberation times and decay characteristics. When investigating, for instance, ideal reverberation time or for a specific type of music, the advantage of this method is that the basic system, hall geometry, overall diffusivity, and the like remain constant whereby the one parameter, the reverberation time, is somewhat isolated and thereby easier to judge. Evidently such experiments do not include different size halls and thus recommendations of reverberation time do not stretch across hall volume.

Surveys have also been done of existing halls through interviews of people who have experience with the acoustics in many halls. These subjective “measurements,” often in the shape of a questionnaire the participants are asked to fill out, are then correlated with objective, acoustic measurements of the halls. One drawback of this method is that acoustic memory for some people is short and can be colored by many nonacoustic factors. This can make the comparison of halls imprecise. Therefore great care must be taken when choosing the test persons and when interviewing them. Those who don’t feel completely capable of performing the interview, and with certainty be able to remember the acoustics of certain halls, must be told not to participate in the investigation regarding those halls. Such extremely professional and experienced individuals who end up participating in the survey have trained their sense of hearing as well as their acoustic memory to a very high level, in many cases without even knowing it. This method of subjective responses to actual halls from memory was selected in the study leading to the recommendations later in this book, primarily because it was deemed to be important to avoid the lack of acoustical information connected with the two other methods mentioned above but also because the author had an extensive network among musicians and sound engineers and thus the investigation was relatively easily set up.

During the twentieth century acousticians have introduced a number of words that characterize a set of acoustical attributes that have proven to be of importance when seeking to describe halls for symphonic music, opera, and other classical music genres. This has enabled acousticians and musicians to share a common vocabulary and thereby to communicate in a somewhat unambiguous way. Doelle (1972), Barron (1993), and Beranek (1996) have provided a list of musical/acoustical terms listed, among others, in *Architectural Acoustics* by Marshall Long (2006). Please see Table 2.1. Each of the terms is associated with at least one measureable acoustical property of a hall. A few of these terms are used in the chapter on the design of halls for amplified music and certainly some of the terminologies are useful when discussing auditorium acoustics in general.

Likewise, in classical music concert halls at least five independent acoustic qualities have been found. These are acoustic properties that the human ear is able to identify isolated from one another. This work was primarily done by Hawkes and Douglas (1971) and as articulated by Michael Barron (2010) discussing the five qualities: “The major concerns are that the *clarity* should be adequate to

Table 2.1 Commonly employed musical and acoustical terms and their definitions

Term	Definition
Balance	Equal loudness among the various orchestral and vocal participants
Blend	A harmonious mixture of orchestral sounds
Brilliance	A bright, clear, ringing sound, rich in harmonics, with slowly decaying high-frequency components
Clarity	The degree to which rapidly occurring individual sounds are distinguishable
Definition	Same as clarity
Dry or dead	Lacking reverberation (little reverberation ^a)
Dynamic range	The range of sound levels heard in the hall (or recording); dependent on the difference between the loudest level and the lowest background level in a space
Echo	A long delayed reflection of sufficient loudness returned to the listener
Ensemble	The perception that musicians can easily play together ^b
Envelopment	The impression that sound is arriving from all directions and surrounding the listener
Glare	High-frequency harshness, due to reflection from flat surfaces
Immediacy	The sense that a hall responds quickly to a note. This depends on early reflections returned to the musician
Liveness	The same as reverberation above 350 Hz
Presence/intimacy ^b	The sense that we are close to the source, based on a high direct-to-reverberant level
Reverberation	The sound that remains in the room after the source has been turned off. It is characterized by the reverberation time
Spaciousness	The perceived widening of the source beyond its visible limits. The apparent source width is another descriptor
Texture	The subjective impression that a listener receives from the sequence of reflections returned by the hall
Timbre	The quality of sound that distinguishes one instrument from another
Tonal color	The contents of harmonics or overtones and their strength relative to the fundamental of a tone ^b
Tonal quality	The beauty or fullness of tone in a space. It can be marred by unwanted noises or resonances in the hall
Uniformity	The evenness of sound distribution
Warmth	Low-frequency reverberation, between 75 Hz and 350 Hz

^aAdded by the author. For instance, a quite dead room at low frequencies is favorable for amplified music

^bAdded/alterd by Jens Holger Rindel

enable musical detail to be appreciated, that the *reverberant response* of the room should be suitable, that the sound should provide the listener with an *impression of space*, that the listener should sense the acoustic experience as *intimate* and that he/she should judge it as having adequate *loudness*.” In this short summary a part of the challenge of auditorium acoustics becomes apparent: although clarity and intimacy, to a large extent, call for a low reverberation time, the factors of reverberant response and impression of space, as well as (acoustic) loudness call for a longer reverberation time. Acoustical consultants operate within a narrow window in order to get all parameters right in a given space.

These principal acoustical subjective qualities have been determined from the questionnaire investigations mentioned earlier. Such investigations have led to an understanding of basic important properties of reflections of sound from boundaries and the like in a room. The late, most quiet reflections are inaudible whereas strong and delayed single reflections are perceived as disturbing echoes. One of the pioneers in these investigations was Helmuth Haas who in 1951 found that the human ear uses the first arriving sound to locate its position and later reflections, even up to approximately 10 dB louder still will appear to stem from the origin, if they are delayed up to some 50 ms compared to the direct sound. This is used advantageously in connection with PA speaker coverage in order to make the emitted sound seem to originate from the orchestra.

Harold Marshall proposed in the late 1960s that early reflections are important and that lateral reflections, meaning reflections from walls or other somewhat vertical surfaces, are the most important. Later Barron and Marshall found that the louder the sound is, and the higher the proportion of lateral sound, the greater is the perceived source broadening. Later investigations by Morimoto and Maekwa and by Soulodre and Bradley showed that there are two such spatial effects occurring, both stemming from lateral reflections: the early sound gives a sense of source broadening and the later reflections create a sense by the listener of being enveloped in sound (Barron). This sense of being inside the sound is believed to have an importance in pop and rock venues too, at least for the musicians and probably also the audience. This is discussed further in [Chap. 5](#). Both source broadening and envelopment are connected to the term “spaciousness” listed in [Table 2.1](#).

Marshall Long lists in his book eight parameters concerning the listening environment itself in halls for music. Later Barron investigated different acoustic spaces in detail, but halls for amplified music do not occupy a specific chapter as do acoustics for synagogues or music practice rooms, for example. He notes that in halls for music:

- The audience should feel *enveloped* or surrounded by sound. This requires strong lateral reflections with a significant fraction arriving from the side.
- The room should support instrumental sound by providing a *reverberant* field whose duration depends on the type of music being played. *A reverberation time that rises with decreasing frequency below 500 Hz yields a pleasant sense of musical warmth.*¹
- There must be *clarity* and definition in the rapid musical passages so that they can be appreciated in detail. This requires reflections from supporting surfaces

¹ In order to avoid any misunderstanding it is pointed out that the higher value of reverberation time at low frequencies proposed here (and in many other textbooks on room acoustics) which some people find beneficial for classical music is the worst enemy of the acoustics for pop and rock music. This is derived in [Chap. 5](#). Furthermore, the PA speaker system is responsible for carrying out the sound at amplified music concerts, not the hall itself, therefore the loudness factor is generally not important in halls for pop and rock music.

located close to the source or the receiver so that the initial time delay gap is short.

- Sound must have adequate *loudness* that is evenly distributed throughout the hall. When the number of seats becomes excessive (above 2,600 seats), loudness and definition are reduced. In small auditoria the loudness must not be overbearing.
- A wide *bandwidth* must be supported. Musical instruments generate sounds from 30 to 12,000 Hz which is much broader than the speech spectrum. The room must not colour the natural spectrum of the music.
- The detailed *reverberation characteristics* of the space should be well controlled with a smooth reverberant tail and no echoes, shadowing coloration or other defects.
- The *performers* should have the ability to hear each other clearly and to receive from the space a reverberant return that is close to that experienced by the audience.
- *Noise* from exterior sources and mechanical equipment must be controlled so that the quietest instrumental sound can be heard.

The above-mentioned subjective parameters are at any given listener position affected by the general design of the classical music hall. Some of these general perspectives are, of course, hall size, hall shape, interior geometry, hall volume, surface materials, balconies and overhangs, seating, and platforms. This is discussed with respect to the design of pop and rock venues in [Chap. 6](#).

Objective Parameters

Various objective parameters, other than reverberation time and EDT, have been defined in an attempt to better describe sound in rooms. The following objective parameters are commonly used and have been shown to be in good agreement with some of the subjective parameters mentioned above.

EDT, Reverberation Time, Liveliness, and Reverberance

Ever since it was defined by Sabine, reverberation time has been the single most important objective acoustic parameter. Whether targeting a reverberation time for an empty hall or a hall with an audience, the reverberation time is the parameter that rooms and halls are designed from based on knowledge of absorption coefficients of different building materials, the volume of the hall, and its purpose. Furthermore, in room acoustics with computer modeling programs including Odeon and Catt among others, more precise calculations can be undertaken by including the modeling of how the sound waves behave in their meeting with surfaces in a room. The

reverberation time is defined by a 60-dB decay and the measurement of it is (as earlier mentioned) based on a 30-dB decay from -5 to -35 dB or even a 20-dB decay.

The early decay time is an expression of reverberation time but based on the decay from 0 to -10 dB and has proven to be better correlated with a test person's judgment of reverberation than T_{30} . A 60-dB, or even a 30-dB, decay is rarely encountered in music because new notes will be played before one gets a chance to hear the full decay of the first note. Although pop and rock music can be highly percussive and syncopated with at least a loud and clear backbeat on the snare drum and a usually somewhat less pronounced downbeat on bass and bass drum, a full 60-dB decay will be seldom encountered. Even an isolated 30-dB decay from -5 to -35 dB is not often heard because it will be masked by other sounds, and therefore EDT is a good descriptor of *reverberance* which is the term used to describe the subjective experience of reverberation. The term *running reverberation* is used for EDT and describes the liveness, or liveliness, of the room.

If the full decay in a hall is perfectly linear, the EDT and T_{30} are the same. EDT is heavily dependent on position in the room where T_{30} is more stable. It can be very short, for instance, under balconies and the like, where the strongest reflections come from large surfaces close to the microphone that do not form the actual room. In such places the decay tail will be steep in its first stage and thereafter flatten out and attain a value in accordance with the T_{30} of the room. This effect is also called the *coupled rooms effect* inasmuch as the first part of the decay takes the shape of the closest "room" with a short reverberation time but dies out in an adjacent room that also has been acoustically evoked and has a longer reverberation. It's easily comprehended by clapping one's hands once in an acoustically quite dead room close to an open door that leads to a room with more lively acoustics.

EDT is the best objective parameter describing a listener's judgment of reverberance while the music is playing. Therefore a room with a seemingly too long T_{30} may actually be acceptable if the EDT is shorter. This is one reason why the ratio EDT: T_{30} is relevant. Furthermore the ratio is a measure for the diffuseness of a room. If the sound in a room is very well diffused the ratio should be close to 1 because a diffuse room is characterized by a linear decay. As a matter of fact it has been shown that a longer reverberation time than expected can be accepted for a room for music if the room is well diffused. In a room design where early energy is directed towards the rear of the hall the ratio is often smaller than 1.

C_{80} , D_{50} , Early Reflections, Clarity, and Intimacy

The early reflections have been found to have an important influence on our impression of reflected sound as containing the qualities of clarity and intimacy. Therefore a parameter describing spaces with early reflections compared to later reflections is a measure of these qualities. Objective clarity is simply the ratio of

early to late sound energy at a given position. The most common measure is C₈₀ for which, as the name indicates, the cut between early and late energy is made at 80 ms; sound arriving before this is considered as early whereas energy that arrives later is defined as late energy. But other definitions are used such as D₅₀, where 50 refers to the cut being applied at 50 ms and *D* is called definition (in German: *deutlichkeit*). Pop and rock music are often highly syncopated musical genres where even 50 ms seems to be too high a value when noting that sound travels 17 m in 50 ms or 8 m to a reflective surface and 8 m back. It has therefore been suggested by the author to investigate shorter time spans.

According to Barron there is evidence that the ear's response to low tones in the 125- and 250-Hz octave bands is slow, wherefore objective clarity is usually calculated as an average of the 500-, 1-k, and 2-kHz bands. As shown in [Chap. 5](#), bass clarity is indeed of importance in pop and rock music although the objective characterization can be of another type than the C₈₀ or D₅₀ parameters at low tones. Objective clarity is a fraction and is expressed in dB. Clarity is inversely proportional to reverberation.

LF, Envelopment, and Lateral Reflections

Reflections from vertical boundaries such as walls are of importance in order for listeners to obtain a sensation of being enveloped in sound. It has been found that particularly the later-arriving lateral reflections are the ones most responsible for this sensation. It is believed that also in pop and rock music especially the performers but probably the audience as well want this acoustic attribute although there has been no specific study made to witness this. It is a fact though that at least some sound engineers prefer clarity to a degree where almost no envelopment can be apparent. The lateral energy fraction in dB is measured with two microphones, one being a figure-eight microphone directed with its zero towards the source and the other being an omnidirectional microphone. The fraction of these two gives an idea of how much sound energy comes from the sides. Of course another way of more rapidly and less precisely finding out about these attributes is simply to take notice of whether the side walls of a room are heavily absorptive or whether the ceiling is relatively low compared to the width of the room. Lateral fraction (LF) is a ratio and is unitless. Envelopment is proportional to reverberation.

G, Strength, and Room Gain

At unamplified concerts the hall alone must bring forward the sound to a degree where the audience even in the back of the hall experiences an appropriate sound level of the acoustic information brought forward from the stage. On the contrary,

in smaller recital halls a large orchestra playing *fortissimo* (very loud) will sound too loud and the loudness of the room becomes overwhelming. The objective measure for the acoustic gain of a room is called strength with the symbol G . G is also known as the room gain.

G of a hall equals the ratio between the SPL of an omnidirectional sound source at a calibrated level at 10 m distance from the source, and the same source, at the same level, at the same distance in an anechoic room.

According to theory, the value of G decreases by 3 dB by doubling the total absorption in the space. The absorption in concert halls is not measured directly and therefore the room gain is computed from the ratio of the reverberation time and the volume of the hall. This makes it clear that increasing the reverberation time of a hall also makes it louder and vice versa. The strength of the reverberant field is often of interest and is denoted G_{late} .

As mentioned earlier, G is not of importance in halls for amplified music because the speaker system is dimensioned to provide enough level although a certain room gain may be beneficial in the 63-Hz band. In overly dampened halls for amplified music, delay speakers must be applied supplementary to the main PA system in order to make up for the sound energy being lost rapidly as it propagates through the hall. This seems like an undesirable design, wasting resources. Of course delay speakers may advantageously be used in very long halls. G is proportional to reverberation.

Bass Ratio, Warmth, and Bass Response

Some people prefer a rise in low-frequency (LF) reverberation time in halls for symphonic music so that at 125 Hz a value of a factor of up to 1.4 times that at mid-frequencies is attained. Evidently this will increase the level of the bass or at least guarantee that the musicians playing the low tones do not have to play unnaturally loud to achieve an acceptable level and blend. Indeed a large number of double-bass players are needed in very large orchestras in order to achieve a sufficient sound level. The rise should in any case bring a sense of “warmth” to the music preferred by some. The “warmth” parameter was suggested by Leo L. Beranek and used by John O’Keefe, for instance.

Beranek has proposed the parameter *Bass Ratio* computed as $BR = (T_{125} + T_{250}) / (T_{500} + T_{1k})$.

In pop and rock music there is a much higher level in the 63-Hz band compared to classical music. But as it turns out, the reverberation time in the 63-Hz band can be justified longer here than in the 125-Hz octave band, also in halls for amplified music. In the appendix of this book two different BR are calculated, one exclusively including the 125-Hz band versus mid-frequencies and one also including the 63-Hz band versus middle frequencies. Other BRs can be calculated depending on what is being investigated. In pop and rock music the 250-Hz band is not really perceived as bass but rather as a mid-low range.

Similarly, the BR can also be defined from the strength G instead of reverberation time, thus referring to the sound in the steady-state condition instead of the decaying sound. Some researchers find this BR more relevant for a concert hall.

ST, Support, and Ensemble

The stage parameter “support” was suggested by Gade in the 1980s. The support parameter ST describes the sound energy returning to the musicians on stage. Skålevik has gathered information about acoustic parameters on his website:

- ST_{early} The early, reflected 20–100-ms sound energy level relative to the initial 0–10 ms direct sound, measured at 1.0 m from an omnidirectional source.
- ST_{late} The late, reflected 100–1,000-ms sound energy level relative to the initial 0–10-ms direct sound, measured at 1.0 m from an omnidirectional source.

The early support, ST_{early} , is now commonly used to describe the degree of *mutual hearing*, also referred to as *ensemble*, on stage. On most stages the early reflected energy is expected to contain sound from the whole ensemble as well as the musician’s own instrument.

The late support describes the degree to which the musician hears the late reverberant sound. ST_{late} is suggested as a descriptor of the performer’s subjective reverberance. Singers often appreciate hearing their own voices filling the auditorium and they often prefer high ST_{late} values. ST_{late} is almost solely determined by the ratio between RT and volume of the hall.

However, one should take the balance $ST_{\text{late}}-ST_{\text{early}}$ into account, because if ST_{late} is high compared to other halls, the late reverberant sound may still appear weak if ST_{early} is also very high. If this balance is too low (say $\ll -3$ dB) musicians may feel that the stage is acoustically decoupled from the auditorium. This may be the result when introducing a canopy that is too low and too dense. Likewise, it seems evident that the ST_{early} value should be considered in relation to ST_{late} . If there is not enough early sound compared to late, the musician may feel not in touch with his or her instrument and this can harm his or her timing. Mutual hearing conditions on a stage can’t be fully measured or predicted with an omnidirectional source on an empty stage because instruments do not radiate sound omnidirectionally and because musicians have an impact on the acoustics on stage both in terms of absorption but also because they block the sound propagation. For symphonic music Christopher Blair notes: “The art of designing good on-stage acoustics boils down to providing just enough early energy to help with coordination, but not so much as to mask audibility of the late-energy room response.”

This parameter indeed also has relevance for amplified music. More support on stage from the immediate surroundings in a given hall lowers the need for loud monitor speaker levels and gives the musicians a feeling of being more enveloped in sound from their own and their colleagues’ instruments, rather than that stemming from the PA system and reflecting surfaces farther away. This is of major

importance for the musicians to enjoy the hall in general. The author finds that the acoustics must be similar on stage to that of the audience area, and that these two spaces must not be acoustically separated. This will automatically lead to louder early reflections than later reflections as perceived by the musicians because of the distance law (sound level decays over distance). In other terms, ST_{early} must be stronger than ST_{late} . This is sometimes a challenge to achieve inasmuch as sound engineers especially (definitely no musicians) want the stage dead to easily handle feedback and the like. This is dealt with in more detail in later chapters.

Late support is proportional to reverberation.