From the Musicians' Perspective: A Brief History of Stage Acoustics

E. K. Ellington Scott

Introduction

Architectural acoustics has played a significant role in tailoring the auditory experiences of concert halls, opera houses, and other musical spaces around the world (see Scarbrough, 2023, p. 43 in this issue). Planning for these spaces, designs, and implementations typically focuses on the audience experience. However, a successful performance starts from the stage. Without a proper stage, musicians may feel they cannot hear themselves or others. A bad design may also force a musician to play excessively loud, which may cause playing out of tune or out of sync with others. Correct enclosure design, material placement, distribution of geometric elements, and many other variables all create a desirable stage experience for the musician. It should also be considered that a musician is not only passively listening to the instruments and voices around them, but there is also an active listening component where the musician is critically listening and playing their instrument. The musician also listens to themselves and others while playing. This requires far more focus and cognitive load than passively listening from the audience. Such a dramatic difference calls for a study dedicated to their auditory experience.

Musicians and vocalists must trust the stage (and the interaction of the stage with the hall) to provide them with feedback from the environment to understand the dynamics, timbre, balance, and blend of their performance with others on the stage. Indeed, professional musicians may constantly adapt from the feedback, or response, from a less-than-ideal acoustic environment that they are more familiar with, but adapting is more difficult for touring or visiting performers because they have minimal experience with new acoustic environments. The inability of an orchestra or soloist to adjust to a lack of response with the performance venue will inhibit them from interpreting their sound as they might when performing on a familiar stage. Thus, not being able to fully adjust to a new space in which an orchestra or soloist is performing may ultimately affect the experience of the audience.
Researchers, acoustic consultants, and other acousticians have developed parameters to describe the acoustic phenomena of spaces to help remedy some of the issues that prohibit an exemplary musical performance, a better aural experience, and an improved response from the hall.

At the same time, the acoustic and auditory needs of the musician may be considered less because the focus of these parameters has not been from the perspective of the musician, but it has, instead, been dominated by the audience's auditory experience. These acoustic parameters are also often correlated to subjective attributes, judgments, and auditory experiences of the audience. However, rather than focus on the audience experience, this article focuses on and describes various examinations and landmark studies of stage acoustics conducted by esteemed acousticians. The development of objective parameters and the correlation to subjective attributes and preferences of stage acoustics are also explored. Additionally, the advancement of standardized measurements utilizing spatial measurement techniques is also reviewed.

A Musician's Auditory System

Before considering objective criteria to evaluate stage acoustics, we must investigate the perceptual effects that may impact how a musician or vocalist perceives sound on the stage of a performance venue.

Masking

One of the most prominent effects is masking. Auditory masking occurs when an auditory event or perceived sound is affected by another auditory event, referred to as the masker. The presence of a masker can reduce the

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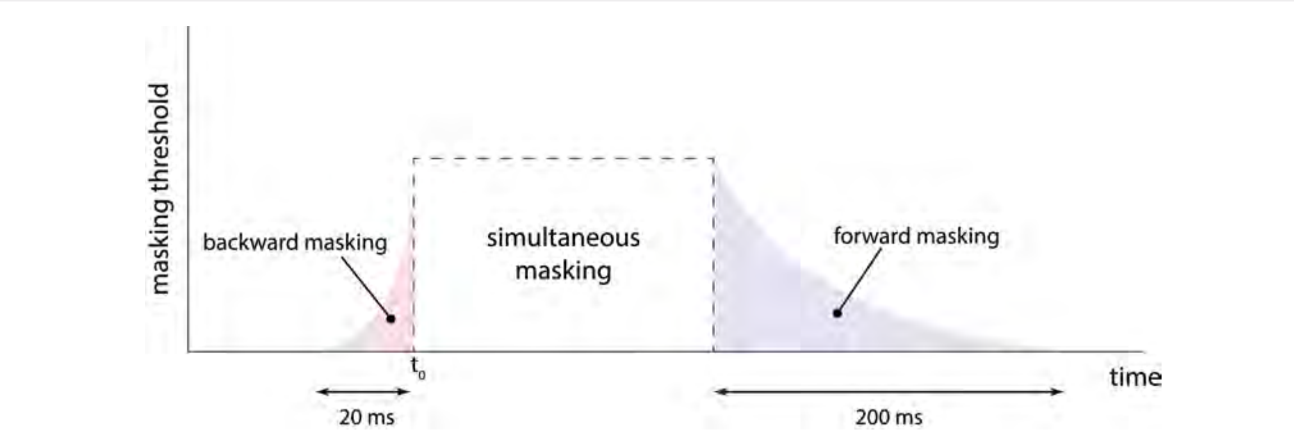


Figure 1. *Illustration of simultaneous and temporal masking. Onset of the masker,* t_0. *Forward masking occurs when the masker has been stopped and the signal is reduced or inaudible within 200 ms. Backward masking occurs when the signal is masked by a subsequent masker within 20 ms.*

loudness of the sound or completely render it inaudible (Fastl and Zwicker, 2007). Within this context, loudness is defined as a subjective sensation correlated to the sound pressure level but is also frequency dependent.

Two types of masking are simultaneous masking and temporal masking. Simultaneous masking describes the phenomenon that occurs when two auditory events, a masker and a signal defined as the sound of interest to the listener, occur at the same time, making the signal difficult to perceive. Temporal masking exists in two basic forms: forward masking and backward masking (**Figure 1**). Forward masking is observed when the listener is trying to perceive a signal just after a masker has ended. This effect can last up to 200 ms after the end of the forward masker. In backward masking, or premasking, the listener's perception of a signal is affected by a masker that is presented after the signal ended; the time window is approximately 20 ms before the end of the signal (Moore, 2014).

Precedence Effect

Another form of signal masking is related to a phenomenon referred to as the precedence effect or the law of first wave front. In normal auditory environments, direct sounds reach a listener's ear and are perceived, while indirect sounds (reflections) reach the ears from different locations (e.g., reflecting off the floor, walls, and ceiling) and with a delay relative to the direct sound (Litovsky et al., 1999). These delayed sounds are not perceived. Engineers designing sound systems for spaces such as auditoria and lecture halls will exploit this phenomenon to enhance the auditory experience for the audience. Sound waves received later from different locations can enhance the auditory experience because they are not perceived as separate auditory objects.

Without proper aligning of the loudspeakers' signals relative to a human speaker, the "fusion" has broken down the sounds into individual auditory events so that the direct and indirect signals appear to be separate. However, even if there are two auditory events within 10 dB (or higher in some cases), the first sound to reach the listener will take precedence in the perceived direction of the auditory event (Panton, 2017). For a musician, if the lagged auditory event is delayed too much, there is no precedence, and echoes are perceived by the musician, causing directional confusion. This limit is known as the echo threshold.

The Cocktail Party Effect

The cocktail party effect (Yost, 2013) is another perceptual effect that characterizes the listener's ability to focus on a single auditory event (e.g., their own music) while surrounded by multiple sound sources (e.g., instruments) from different directions and with different spectral and temporal characteristics. Perhaps the best example of this effect is in its own name. Consider a listener at a cocktail party trying to focus on the speech of another person with whom they are having a conversation (signal), but there are many competing maskers (voices) from multiple directions. It turns out, however, that the location of the signal (speaking companion) may help the listener perceive that source above the masker compared with a situation where the signal and masker are emitted from the same location (Blauert, 1997).

Another important feature of the cocktail party effect is that the frequency and timing differences between the masker and the signal may help a listener pick out the signal from the background noise. Thus, the spatial, spectral, and temporal cues may be particularly helpful for a musician listening to a specific instrument or vocalist within the orchestra or ensemble.

Musicians' Subjective Experience

In his book *Music, Acoustics, and Architecture*, Beranek (1962, p. 73) states, "The technical data about the acoustics of a concert hall tell only a part of the story." There must be a balance between the technical objective study and the subjective study, which often deals with the perception and preference of the acoustic experience in various venues. Subjective studies also allow for a vocabulary describing these perceptual impressions to be produced. These terms or subjective attributes, such as an overall auditory impression, hearing ensemble (the ability to hear others), or reverberance, describe the perceptual preference and judgment of a performance space. Acoustic parameters of the concert hall, such as reverberation time, are meaningless without correlation of a subjective attribute or judgment that describes the auditory experience in the acoustic performance space. The subjective studies measuring these attributes also give acousticians an idea of preference and desirable ranges for measured acoustic parameters. This gives a guide during the design process for a performance space. In fact, acoustic measurements, ethnographic interviews, and perceptual tests all contribute to make a holistic study and design of a space or potential space.

Subjective Studies of Stage Acoustics

Beranek's (1962) initial interviews with musicians, critics, and conductors revealed the importance of reverberation attached to a musician's impression of how their music sounds in a hall. Subsequently, Gade (1981) conducted an exhaustive study, interviewing 32 instrumentalists, conductors, and vocalists, with the goal of refining a vocabulary to describe their acoustic concerns. The finalized vocabulary from these interviews was reverberance, support, timbre, time delay, hearing each other, and dynamics. These terms were compiled from each musician's interviews expressing their acoustic concerns about performance spaces encountered and the relative importance of each.

- *Reverberance* is the perceived reverberation of a space and also describes how notes are connected aurally. It can blur or accentuate the separation of the projected notes of the voice or instrument.
- *Support* details how much the response or feedback of a venue helps "support" the musician or vocalist to produce their desired notes while performing. A venue without proper support can cause a musician to fatigue from having to expend too much mental focus and physical energy to project their desired sound.
- *Timbre* relates to the color or tonal quality influenced by the spectral properties of the room. Each hall emphasizes or extenuates certain frequency ranges, giving a unique coloration of sound in each performance space.
- *Time delay* is a consequence of the distance between ensemble members. The greater the distance between musicians, the more difficult for the performers to play together with respect to time and rhythm (rhythmic synchronicity).
- *Dynamics* corresponds to how the room interacts with the perceived loudness of the instrument and how it relates to the intention of the musician's desired loudness. In other words, does the intended dynamic of the musician correspond to the dynamic received from the response of the hall?

To summarize the various subjective attributes required for the musician to play on stage, Meyer (1994, 2009) addressed the acoustic needs necessary to engage in desirable stage communication. There are three levels of quality.

(1) The first degree represents the need of the musician to play correctly. A projected sound that is late compared with other musicians degrades the rhythmic integrity and precision of the performance. Moreover, a sound that is too soft relative to other musicians degrades the intonation and clarity of the projected note.

(2) The second degree describes the sound quality of the musician's instrument beyond the projected note. A good overall auditory impression within a venue allows for ease of playing and hearing the ensemble. In other words, the hall allows the musician or vocalist to easily project within a space

without too much mental focus centered toward the first degree mentioned above, allowing more nuance and character in the projected note. This, in turn, increases the dynamic range, unforced playing, and blends with the ensemble.

(3) The third degree represents the ensemble or orchestra. It describes the ability of the sections of the ensemble to blend and integrate melody and harmony, particularly the strings. To achieve this balance within the ensemble, the conductor's position plays an important role in hearing each of these sections and ensuring they are well-balanced from the stage.

Ueno et al. (2005) conducted similar interviews directed toward smaller ensembles. These interviews and discussions highlighted the acoustical needs of a performer while playing in a smaller ensemble, such as a chamber music ensemble. The study found that hearing each other and making harmony were the two crucial qualities needed for a successful performance. Hearing each other was described as hearing both themselves and the other performers. Making harmony illustrates the necessity to blend and not separate projected notes to harmony and unified sound (Ueno et al., 2005).

Proposed Stage Acoustic Parameters

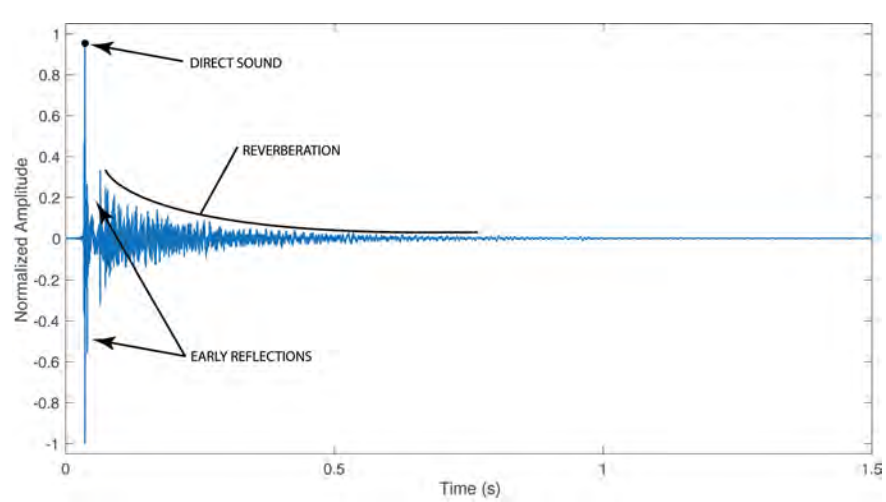
The subjective studies of experiences on the stage has garnered enough momentum to propose stage acoustic parameters. A landmark study by Marshall et al. (1978) introduced the importance of early reflections for ease of playing when a soloist performs with an orchestra. Early reflections, especially in the high-frequency range, from the walls of the stage enclosure, reflectors, ceilings, or underside of the balcony contribute to the musician's ability to play with ease within a venue (Marshall et al., 1978).

Stage Support

The most widely used stage acoustic parameters were determined by Gade (1989a) during his study of support to assess soloistic and ensemble conditions. Gade proposed three acoustic parameters describing stage support: early stage support (ST_{early}), late stage support (ST_{late}), and total stage support (ST_{total}).

These parameters are calculated using a measured impulse response (**Figure 2**). The impulse response uniquely characterizes the temporal and spectral properties of each venue or even each seat position within the venue. Because the square of the measured pressure from the impulse response is proportional to the energy, many parameters take advantage of this, comparing the energy of different time segments of the impulse responses. The stage support parameters compare energy in the early (20-100 ms), late (100-1,000 ms), and total (20-1,000 ms) time segments of the impulse response. The measurement is performed with a receiver (microphone) position of 1 m, approximating a direct instrument-to-ear sound path of most instruments (Gade, 1989a).

Figure 2. *Example of impulse response measured in a concert hall. The impulse response is typically divided into three regions: (1) direct sound, which is the path directly from the source to the receiver, (2) early reflections from the floor, wall, ceiling, and other surfaces; and (3) reverberation, which are more dense, smaller reflections similar to a noise-like signal.*



A further study by Gade (1989b) showed a high correlation between the stage support acoustic parameters and the subjective attributes expressed by the musicians for describing overall auditory quality and timbre. However, investigations by Kim et al. (2007) showed a wide variation of stage support across one stage, questioning the reliability of the acoustic parameters that had been determined. Kim and colleagues suggested changing the time segment used to calculate stage support to omit the direct sound of the impulse response, creating more consistency in the measurement. Nonetheless, the stage support parameters are all included in the International Organization for Standardization (ISO) 3382-1:2009 (2021) for acoustics measurements in performance spaces.

In the 2000s, Dammerud investigated many various audience-focused parameters to apply them to stage acoustics. In particular, he studied the strength parameter (*G*). Originally developed to measure loudness by the audience, Dammerud (2009) determined two variations of the strength parameter, G_{early} and G_{late}. Each variation was used to determine the strength of a signal across the stage during orchestral conditions at certain time segments of the impulse response. Similar to the stage support, the variations in strength focusing on the stage acoustics used energy ratios to understand the perceived loudness on stage (Dammerud, 2009).

Spatial Acoustic Parameters

The parameters mentioned in ***Stage Support*** are normally measured using a microphone that is omnidirectional. This means that the transducer is equally sensitive in a desired frequency range to all directions while recording the acoustic measurement. However, some microphones can weigh in different directions, allowing spatial impulse-response measurements of a sound field and spatial acoustic parameters. Only two spatial parameters are presented in ISO 3382-1:2009 (2021) the interaural cross-correlation coefficient (IACC) and lateral fraction (LF). These are calculated utilizing an impulse-response measurement from a binaural dummy head (see Paul, 2009) for the IACC and a combination of various microphones for the LF. However, the standardized measurements are correlated more toward the audience experience.

The growing popularity of spherical microphone arrays (**Figure 3**) has allowed a more comprehensive study of three-dimensional sound fields. Explicitly, spherical microphone arrays allow the user to understand the directional characteristics of a sound field by using spatial filtering. Spatial filtering, known as beamforming, applies a combination of weights to the measured signals from the spherical microphone array to point in a specific azimuthal (horizontal) and elevation angle. This enables the user to essentially point a virtual beam with user-defined horizontal and vertical angles to determine the sound field in that particular direction. In research done by Guthrie (2014) and Panton (2017), combinations of these beams were used to determine the directional behavior of stage acoustics parameters. In doing so, the homogeneity of various stage acoustics parameters can be realized in all directions on the stage.

Figure 3. *Example of a spherical microphone array. The black object has 19 microphone capsules embedded in a rigid body. For more information about the placement of the microphone capsules, design, and implementation of spherical microphone arrays, see Rafaely (2019).*

Auralizations

Another advantage of using spherical microphone arrays for acoustical measurements is the application of laboratory-controlled experiments. Historically, auralizations ("aural visualization") were rendered using binaural impulse-response measurements. But, the spherical microphone array enables measurements to re-create the physical sound field using a spatial audio technique called Ambisonics (see ambisonic.info/index.html).

Ambisonics is a spherical playback format that produces a three-dimensional sound field to enable spatialization of a virtual or recorded sound. By convolution, anechoic ("no echo" or no reflection) recordings of music, speech, or soundscapes can be rendered as if they were in the space that has been measured. In other words, the convolution applies the temporal and spectral effects of the acoustic venue to the anechoic recordings to simulate a desired position on stage (or in the audience). This allows for direct comparison between acoustic spaces without depending on the auditory memory of the subject (Panton, 2017). Consequently, musicians can compare auditory experiences of concert halls directly without depending on the memory of performances.

Summary

Stage acoustics is an essential part of architectural acoustics to enhance and better the experience for the performer as well as for the audience. Although stage geometry and enclosures are thoroughly designed, the correlation of subjective attributes from the musician's perspective and object parameters is still a complex, multidimensional problem. This article covered only a few of the studies on the topic to introduce the reader to a vast field that has only been studied on the surface.

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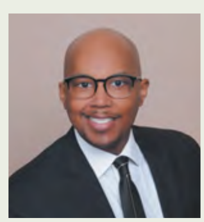
Contact Information



E. K. Ellington Scott
escott@arlut.utexas.edu
Applied Research Laboratories
The University of Texas at Austin
10000 Burnet Road
Austin, Texas 78758, USA

For author bio, please go to acousticstoday.org/bios-19-4-5