The Art of Concert Hall Acoustics: Current Trends and Questions in Research and Design

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Concert hall design exists at the intersection of art, science and engineering, where acousticians continue to demystify aural excellence.

What defines "excellence" in concert hall acoustics? Acousticians have been seeking perceptual and physical answers to this question for over a century. Despite the wealth of insightful research and experience gained in this time, it remains established canon that the best concert halls for classical orchestral performance are the Vienna Musikverein (1870), Royal Concertgebouw in Amsterdam (1888), and Boston Symphony Hall (1900; Beranek, 2004). Built within a few decades of each other, the acoustical triumph of these halls is largely attributable to their fortuitous "shoebox" shape and emulation of other successful halls. Today, we have a significantly more robust understanding of how concert halls convey the sounds of musical instruments, and we collect tremendous amounts of perceptual and physical data to attempt to explain this phenomenon, but in many respects, the definition of excellence remains elusive.

This article discusses current trends in concert hall acoustical design, including topics that are well understood and questions that have yet to be answered, and challenges the notion that "excellence" can be defined by a single room shape or set of numerical parameters.

How Should a Concert Hall Sound?

This is the fundamental question asked at the outset of every concert hall project, but it is surprisingly difficult to answer succinctly. The primary purpose of a concert hall is to provide a medium for communication between musicians and the audience (Blauert, 2018). There are several percepts of the acoustical experience, different for musicians and listeners, that are critical for enabling this exchange. On stage, musicians need good working conditions so that they hear an appropriate balance of themselves, each other, and the room. For a listener in the audience, articulating the goals is more difficult.

Listeners want to be engaged actively by the music, but the acoustical implications of this goal are complex and highly subjective. This question has been the focus of rich and diverse research for decades, including notable contributions by Beranek (1962, 1996, 2004; summarized in a previous issue of *Acoustics Today* by Markham, 2014), Hawkes and Douglas (1971), Schroeder et al. (1974), Soulodre and Bradley (1995), and Lokki et al. (2012) among others. These studies have established a common vocabulary of relevant perceptual characteristics and have attempted to distill the correlation between listener preference and perception to a few key factors, but it remains true that acoustical perception in concert halls is multidimensional. Kuusinen and Lokki (2017) recently proposed a "wheel of concert hall acoustics,"

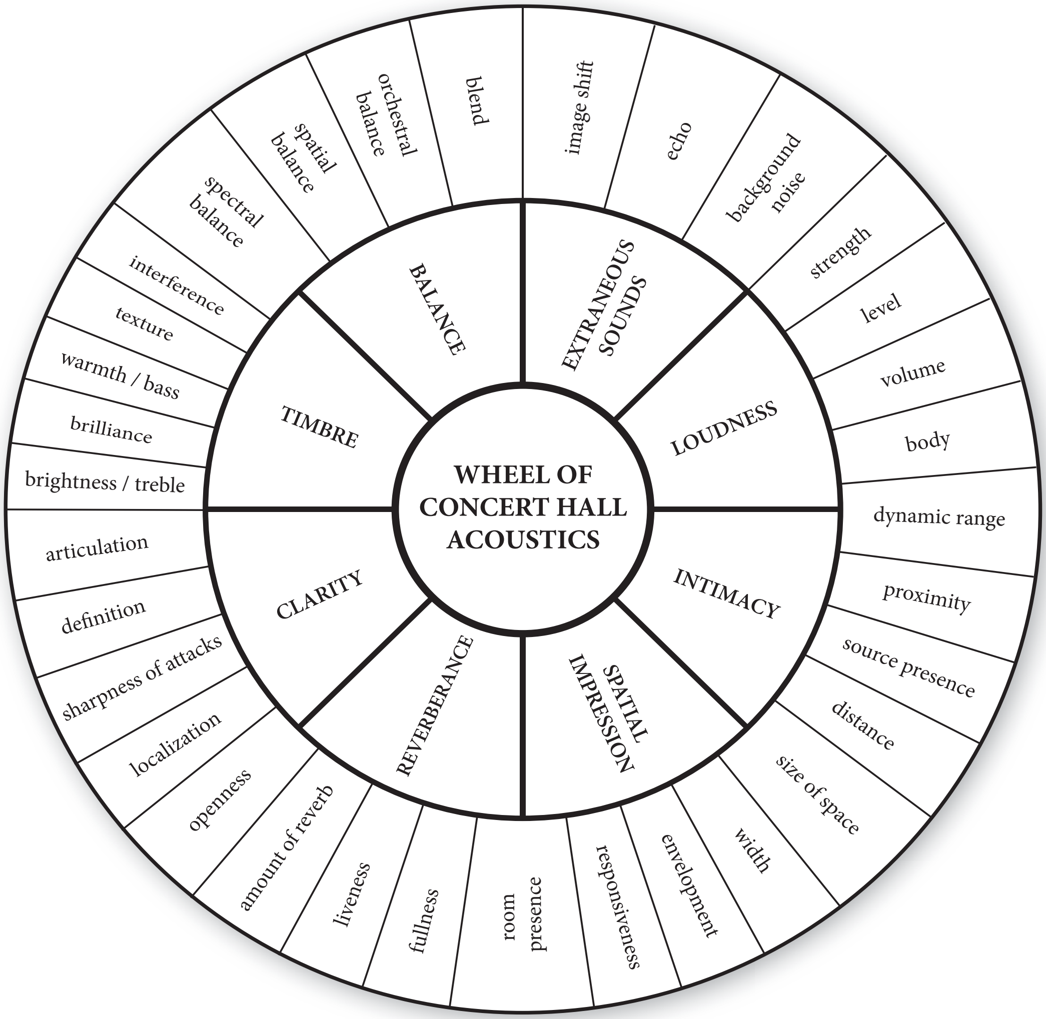

Figure 1. *"Wheel of concert hall acoustics." The graphic proposes a common vocabulary for eight primary attributes (inner ring) of acoustical perception in concert halls, and several related sub-factors (outer ring). Some attributes in the outer ring overlap between primary percepts, illustrating their interdependency. The circular organization highlights the fact that there is not a consensus hierarchy of characteristics correlated with listener preference, and the structure does not assume orthogonality between any pair of perceptual attributes. From Kuusinen and Lokki (2017), with permission from S. Hirzel Verlag.*

shown in **Figure 1,** that groups relevant perceptual factors into eight categories: clarity, reverberance, spatial impression, intimacy, loudness, balance, timbre, and minimization of extraneous sounds.

Although there is not yet a consensus around specific attributes most correlated with audience listener preference, there is agreement that different people prioritize different elements of the acoustical experience. Several studies have shown that listeners can be categorized into at least two preference groups: one that prefers louder, more reverberant and enveloping acoustics and another that prefers a more intimate and clearer sound (Lokki et al., 2012; Beranek, 2016). The listening preferences of the first category generally align with the acoustical features of "shoebox" concert halls (tall, narrow, and rectangular), such as those in Vienna, Boston, and Amsterdam. Among other factors, the second category of listeners may be influenced by perceptual expectations developed from listening to recordings of classical orchestral music rather than attending live performances (Beranek et al., 2011). However, all elements remain important to the listening experience. Even listeners who prefer a clearer sound still require an adequate level of loudness, reverberance, and envelopment (Lokki et al., 2012). Historically, acousticians have considered some percepts, such as reverberance and clarity, to be in direct opposition with each other, but there is new emphasis on finding a common ground to engage more listeners.

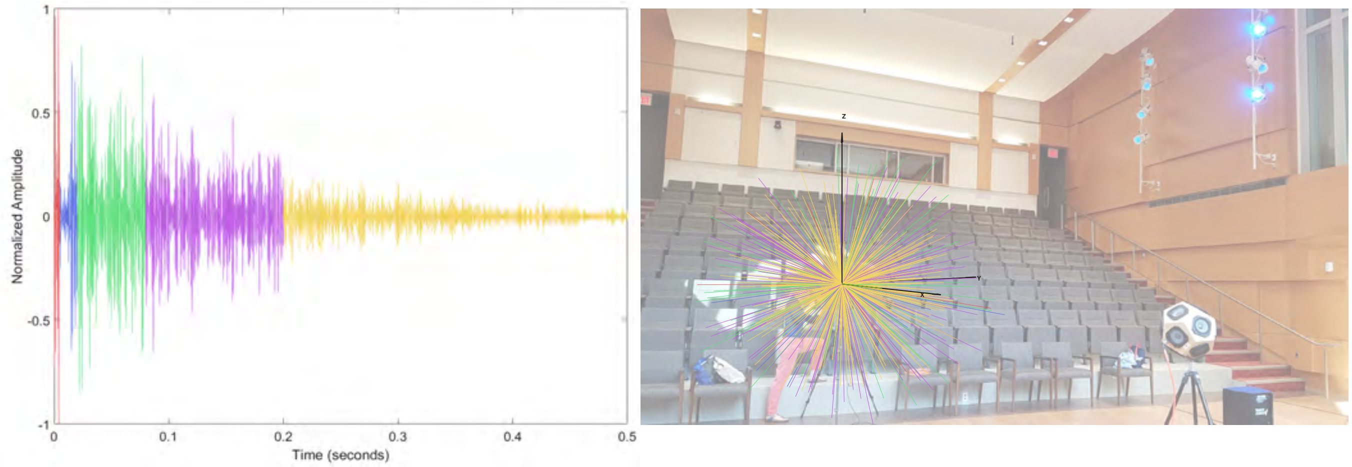

Figure 2. *Measured impulse responses (IRs) from the Rachel Carson Music and Campus Center Recital Hall, Concord, MA. Both IRs were measured with an omnidirectional (dodecahedral) loudspeaker, band-pass filtered in a 1-kHz octave band, and color coded by temporal region.* ***Left:*** *IR, measured with an omnidirectional microphone, shows relative timing and level of reflections arriving from all directions.* ***Right:*** *IR, measured with a multichannel directional microphone, shows relative level and spatial distribution of reflections. Photo by Kelsey Hochgraf.*

Using Auditory Stream Segregation to Decode a Musical Performance

One innovative approach is based on the principles of auditory stream segregation, building on Bregman's (1990) model of auditory scene analysis. According to this model, the brain decomposes complex auditory scenes into separate streams to distinguish sound sources from each other and from the background noise. The "cocktail party effect" is a common example of auditory stream segregation, which describes how a person can selectively focus on a single conversation in a noisy room yet still subconsciously process auditory information from the noise (e.g., the listener will notice if someone across the room says their name). See the discussion of similar issues in classrooms in Leibold's article in this issue of *Acoustics Today*.

In a concert hall, the listener's brain is presented with a complex musical scene that needs to be organized in some way to extract meaning; otherwise, it would be perceived as noise. Supported by research studies at the Institute for Research and Coordination in Acoustics and Music in Paris, Kahle (2013) and others have suggested that the brain decomposes the auditory scene in a concert hall into distinct streams: the source and the room. If listeners can perceive the source separately from the room, then they can perceive clarity of the orchestra while simultaneously experiencing reverberance from the room. Griesinger (1997) has suggested that this stream segregation is contingent on the listener's ability to localize the direct sound from individual instruments separately from other instruments and from reflections in the room. Although the brain may perceive the auditory streams separately, the source and room responses are dependent on each other acoustically. Developing a better understanding of this relationship, both spatially and temporally, is critical to integrating the range of acoustical percepts more holistically in the future.

Setting Acoustical Goals for a New Concert Hall

Without one set of perceptual factors to guarantee acoustical excellence, who determines how a new concert hall should sound? In recent interviews between the author of this article and acousticians around the world, three typical answers emerged: the orchestra, the acoustician, or a combination of both. Scott Pfeiffer, Robert Wolff, and Alban Bassuet discussed the early design process for new concert halls in the United States, which often includes visiting existing spaces so that the orchestra musicians, conductor, acoustician, and architect can listen to concerts together and discuss what they hear. Pfeiffer (personal communication, 2018) expressed the value of creating a "shared language with clients to allow them to steer the acoustic aesthetic." Wolff (personal communication, 2018) mentioned that orchestra musicians often have strong acoustical preferences developed from playing with each other for many years and having frequent opportunities to listen to each other from an audience perspective. Bassuet (personal communication, 2018) asserted that it is more the acoustician's responsibility to "transpose into the musician's head when designing the hall" and set the perceptual goals accordingly.

Table 1. *Summary of standard room acoustics parameters*

Parameter	Description	Intended Perceptual Correlate
Reverberation time (RT, T_{20}, T_{30})	Time for sound to decrease by 60 dB, based on linear fit to energy decay (excluding direct sound and earliest reflections)	N/A
Early decay time (EDT)	Similar to RT, but based on initial 10 dB of decay (including direct sound and earliest reflections)	Reverberance
Strength (G)	Logarithmic ratio between sound energy in room vs. free field 10-m away from the same source	Loudness
Clarity (C_{80})	Logarithmic ratio between early (0-80 ms) and late (after 80 ms) energy	Clarity
Early lateral energy fraction (J_{LF})	Ratio between lateral and total energy within first 80 ms	Apparent source width
Late lateral sound level (L_J)	Logarithmic ratio between late lateral energy (after 80 ms) and total energy	Listener envelopment
Interaural cross-correlation coefficient ($IACC_{Early}$, $IACC_{Late}$)	Binaural measure of similarity between sound at left and right ears, reported separately for early (0-80 ms) and late (after 80 ms) energy	Early: apparent source width Late: listener envelopment
Stage support (ST_{Early}, ST_{Late})	Ratios between reflected and direct sound measured on stage, reported separately for early (20-100 ms) and late (100-1,000 ms) energy	Early: ensemble hearing Late: reverberance on stage

Data from the International Organization for Standardization (ISO, 2009).

Eckhard Kahle (personal communication, 2018) discussed how the early design process differs outside the United States, where project owners often hire independent acousticians to develop an "acoustic brief," and design teams compete against each other to develop a conceptual design that most effectively responds to the acoustical goals outlined by the brief. With such a variety of perceptual factors and approaches to prioritizing them, it is no surprise that concert halls around the world sound as different from each other as they do.

How Can Perceptual Goals be Translated into Quantitative, Measurable Data?

Considering a concert hall as a linear, time-invariant system, an impulse-response measurement can be used to understand how the room modifies the sounds of musical instruments. **Figure 2** shows impulse responses measured with an omnidirectional loudspeaker and two different microphones. The impulse response measured with an omnidirectional microphone (**Figure 2, *left***), illustrates the direct sound path from the loudspeaker to the microphone, early reflections that are strong and distinct from each other and weaker late reflections that occur closely spaced in time and decay smoothly. Measurements are analyzed by octave band and divided temporally, although the time periods most relevant to each percept are the subject of ongoing research. To understand the spatial distribution of reflections around the listener, a multichannel impulse response can be measured with a directional microphone array (**Figure 2, *right***). Several numerical parameters standardized by ISO 3382-1:2009 (International Organization for Standardization [ISO], 2009; summarized in **Table 1**), can be derived from impulse responses measured with an omnidirectional sound source.

There is growing consensus among acousticians that although many of these parameters are useful, they do not provide a complete representation of concert hall acoustics. In an interview with the author of this article, Pfeiffer (personal communication, 2018) noted "there's a range of performance in any of the given parameters that's acceptable, and a range that's not" but that the "mythical holy grail of perfect acoustics" does not exist. Acoustician Paul Scarbrough (personal communication, 2018) noted that standard parameters are particularly limited in describing the spatial distribution of sound, saying "we're not measuring the right things yet." Bassuet (personal communication, 2018) suggested that "we should not be afraid to make connections between emotional value and [new] acoustical metrics." Recent article titles are similarly critical and illustrative: "In Search of a New Paradigm: How Do our Parameters and Measurement Techniques Constrain Approaches to Concert Hall Design" (Kirkegaard and Gulsrund, 2011) and "Throw Away that Standard and Listen: Your Two Ears Work Better" (Lokki, 2013).

Deficiencies of Existing Objective Parameters

In summary, the limitations are largely attributable to differences between an omnidirectional sound source and an orchestra and between omnidirectional microphones and the human hearing system. As described in detail by Meyer (2009), each musical instrument has unique and frequency-dependent radiation characteristics. As musicians vary their dynamics, the spectrum also changes; at higher levels, more overtones are present. These nonlinear radiation characteristics are not represented by an omnidirectional sound source, and the directivity of the sound source has a significant impact on perception of room acoustics (Hochgraf et al., 2017). This problem becomes more pronounced, complicated, and perceptually important when considering the radiation of an entire orchestra.

In the audience, the listener hears the orchestra spatially, not monaurally. Binaural and directional parameters for spatial impression are helpful, but measurement of these parameters can be unreliable due to the impacts of microphone calibration and orientation on the parametric calculation. In addition to directivity mismatches between real sources and receivers and those used to measure impulse responses, the frequency ranges of human hearing and radiation from musical instruments are both significantly larger than the capabilities of most loudspeakers used for room acoustics measurements. Beyond the inherent limitations of the standard parameters, impulse responses are often measured in unoccupied rooms and averaged across multiple seats. Occupied rooms, however, are significantly different acoustically from unoccupied rooms, and acoustical conditions vary significantly between different seats.

As the significance of these limitations has become clearer, acousticians have developed new ways of analyzing impulse responses to obtain useful information. More emphasis is being placed on visual and aural inspection of the impulse response instead of on parameters that can obscure important acoustical details. Acousticians also modify standard parameters in a variety of ways, including changing temporal increments, separating calculation for early and late parts of the impulse response, and averaging over different frequency ranges. Although these adaptations may help an individual acoustician make sense of data, it makes it difficult to compare halls with each other—one of the primary reasons for documenting parameters in the first place.

New parameters are also emerging, including Griesinger's (2011) localization metric (LOC) for predicting the ability of a listener to detect the position of a sound source and Bassuet's (2011) ratios between low/high (LH) and front/rear (FR) lateral energy arriving at the sides of a listener's head. The potential utility of objective metrics that correlate well with perception is undeniable, but as more parameters emerge and their application among acousticians diverges, we are continually faced by the question of whether parameters fundamentally support or suppress excellent design.

Figure 3. *Boston Symphony Hall. Photo by Peter Vanderwarker.*

Figure 4. *Philharmonie de Paris. Photo by Jonah Sacks.*

How Do Perceptual Goals and Parametric Criteria Inform Design?

The form of a concert hall is determined by a variety of factors, including, but not limited to, acoustics. One of the greatest challenges and responsibilities of an acoustician is to educate the design team of the implications of room shape and size, which fundamentally determine the range of possible acoustical outcomes, so that design decisions are well-informed and consistent with the perceptual goals.

Case Studies of Two Concert Halls:
The Influence of Shape, Size, and Parametric Criteria

Boston Symphony Hall (**Figure 3)** and the Philharmonie de Paris (**Figure 4)** were built over a century apart, and although they are used for the same purpose, they are fundamentally different acoustically.

Constructed in 1900, the shoebox shape of Boston Symphony Hall is the result of architectural evolution from royal courts, ballrooms, and the successful, similarly shaped Gewandhaus Hall in Leipzig, Germany (Beranek, 2004). It was the first hall built with any quantitative acoustical design input, courtesy of Wallace Clement Sabine and his timely discovery of the relationship between room volume, materials, and reverberation. Built in 2015, the Philharmonie de Paris is far from rectangular. Its form is most similar to a "vineyard" style hall, which features a centralized orchestra position surrounded by audience seated in shallow balconies. Led by Jean Nouvel (architect) and Harold Marshall (design acoustician), the design team was selected by competition and was provided with a detailed and prescriptive acoustical brief by the owner's acoustician (Kahle Acoustics and Altia, 2006). Sabine's scientifically based acoustical design input for Boston Symphony Hall was limited to its ceiling height. On the other hand, the design of the Philharmonie de Paris was based on decades of research about concert hall acoustics. How do these halls, built under such different circumstances, compare with each other acoustically?

Boston Symphony Hall is known for its generous reverberance, warmth, and enveloping sound. Its 2,625 seats are distributed across a shallowly raked floor and two balconies that wrap around the sides of the room, which measures 18,750 m^3 in total volume. If the seats were rebuilt today, code requirements and current expectations of comfort would significantly reduce the seat count. The lightly upholstered seats are acoustically important for preserving strength and reverberance (Beranek, 2016). Heavy, plaster walls reflect low-frequency energy and help to create a warm timbre. The hard and flat lower side walls and undersides of shallow side balconies provide strong lateral reflections to the orchestra seating level, and statues along the ornamented upper side walls and deeply coffered ceiling promote diffuse late reflections throughout the room. The large volume above the second balcony fosters the development of late reverberation that is long, relatively loud, and decays smoothly. The perception of clarity in the room varies by listening position and the music being performed. The Boston Symphony Orchestra is also one of the world's best orchestras, and it knows how to highlight the hall's acoustical features, particularly for late classical and romantic era repertoire.

The Philharmonie de Paris seats 2,400 in a total volume of 30,500 m^3, which is over 60% larger than Boston Symphony Hall. One of the results of this significant difference in size is that although the Philharmonie's reverberation is long in time, it is lower in level, which strikes a different balance between reverberance and clarity. In an interview with Kahle (personal communication, 2018), he noted that the high seat count was one of the primary acoustical design challenges and this necessitated the parametrically prescriptive design brief. In his words, "an orchestra has a limited sound power, which you have to distribute over more people…and if you share it, you get less of it." The seating arrangement keeps the audience closer to the musicians, which heightens the sense of intimacy. Lateral reflections are provided by balcony fronts, although the distribution of lateral energy and ensemble balance vary more between seats due to the shape of the room and position of the orchestra. Concave wall surfaces are shaped to scatter sound and avoid focusing. The lengthy but relatively less loud reverberation is generated by an outer volume that is not visible to the audience. The same orchestra playing the same repertoire will sound completely different in Paris compared with Boston, and the quality of the listening experience will depend on where one is sitting, the music being performed, and, most of all, the listener's expectations and preferences.

Table 2 shows a comparison of parameters measured in both halls. The numbers show some interesting relative differences but do not convey the perceptual significance of these differences or predict how someone would perceive the acoustics of either hall from a particular seat. Standard deviation from the average measured parameters should be at least as important as the averages, especially for spatial parameters, although this information is rarely published. None of the measured parameters describe timbre, ensemble balance, or blend. Although the parameters do impart meaning, especially in the context of listening observations and an understanding of how architectural features in the room impact the acoustics, they do not describe the complete acoustical story or provide a meaningful account of the halls' dramatic differences.

Table 2. *Average mid-frequency parameters measured in Boston Symphony Hall and Philharmonie de Paris*

	RT_{unocc}, s	RT_{occ}, s	EDT, s	G_{mid}, dB	C_{80}, dB	J_{LF}
Boston Symphony Hall	2.5	1.9	2.4	4.0	−2.6	0.24
Philharmonie de Paris	3.2	2.5	Not reported	2.2	−0.7	0.20

Data for Boston Symphony Hall from Beranek (2004) and for Philharmonie de Paris from Scelo et al. (2015).

Where do we go from here? It can be tempting to conclude that all new concert halls should be shoebox shaped and that the acoustics in more complex geometries remain an unsolvable mystery. But as long as architectural and public demand for creative room shapes continues to grow, we must keep pursuing answers.

Two Emerging Design Trends from Recent Research and Experience

The importance of lateral reflections for spatial impression is well-understood (Barron, 1971; Barron and Marshall, 1981; Lokki et al., 2011), but more recent research has shown that these reflections are also critical to the perception of dynamic responsiveness. Pätynen et al. (2014) have recently shown that lateral reflections increase the perceived dynamic range by emphasizing high-frequency sounds as the result of two important factors: musical instruments radiate more high-frequency harmonics as they are played louder and the human binaural hearing system is directional and more sensitive to high-frequency sound that arrives from the sides. If lateral reflections are present, they will emphasize high-frequency sound radiated from instruments as they crescendo, and our ears, in turn, will emphasize these same frequencies. If they are not present, then the perceived dynamic range will be more limited. Increased perception of dynamic range has also been shown to correlate with increased emotional response (Pätynen and Lokki, 2016).

Building on these developments, Green and Kahle (2018) have recently shown that the perception threshold for lateral reflections decreases with increasing sound level, meaning that more lateral reflections will be perceived by the listener as the music crescendos, further heightening the sense of dynamic responsiveness. From an acoustical design perspective, it is easier to provide strong lateral reflections for a larger audience area in a shoebox hall by simply leaving large areas of the lower side wall surfaces hard, massive, and flat. In a vineyard hall, the design process is more difficult because individual balcony fronts and side wall surfaces are smaller and less evenly impact the audience area.

The role of diffusion has been hotly debated in architectural acoustics for a long time. A diffuse reflection is weaker than a specular reflection and scatters sound in all directions. Diffusion is helpful for avoiding problematic reflection patterns (such as echoes or focusing effects) without adding unwanted sound absorption. It can also be helpful for creating a more uniform late sound field (such as in the upper volume of Boston Symphony Hall). Haan and Fricke (1997) studied the correlation between estimated surface diffusivity and overall acoustical quality perceived by musicians playing in 53 different halls. As a result of the high correlation that they found, as well as design preferences of many acousticians and architects at the time, many halls built in the last two decades have a high degree of surface diffusivity. Not all of these halls have been regarded as acoustically successful, particularly when the articulation has all been at the same physical scale (meaning that surfaces diffuse sound in a narrow range of frequencies) and when the diffusion has weakened lateral reflections that we now better understand to be critical to multiple perceptual factors.

The title of a recent presentation is particularly illustrative of the growing opinion among acousticians who caution against the use of too much diffusion: "Halls without qualities – or the effect of acoustic diffusion" (Kahle, 2018). Although the tide seems to be shifting away from high surface diffusivity and there is more evidence to substantiate the need for strong lateral reflections, there is still limited evidence from research to explain exactly how diffusion impacts the listening experience.

How Will Concert Hall Acoustical Design Change in the Future?

In parallel with applying lessons learned from existing halls, the future of concert hall acoustical design will be transformed by the power of auralization. An auralization is an aural rendering of a simulated or measured space, created by convolving impulse responses with anechoic audio recordings, played over loudspeakers or headphones for spatially realistic listening. Auralizations have been used in research and limited design capacities for several years, but recent technological advancements associated with measurement, simulation, and spatial audio have the potential to leverage auralization for more meaningful and widespread use in the future, potentially answering previously unresolved questions about concert hall acoustical perception and design. Rather than averaging and reducing impulse responses to single number parameters, auralizations strive to preserve all the perceptually important complexities and allow acousticians to make side-by-side comparisons with their best tools: their ears.

Auralizing the design of an unbuilt space requires simulating its impulse response. Commercially available room acoustics software currently relies on geometric simulation methods that model sound waves as rays, which is a valid ap-

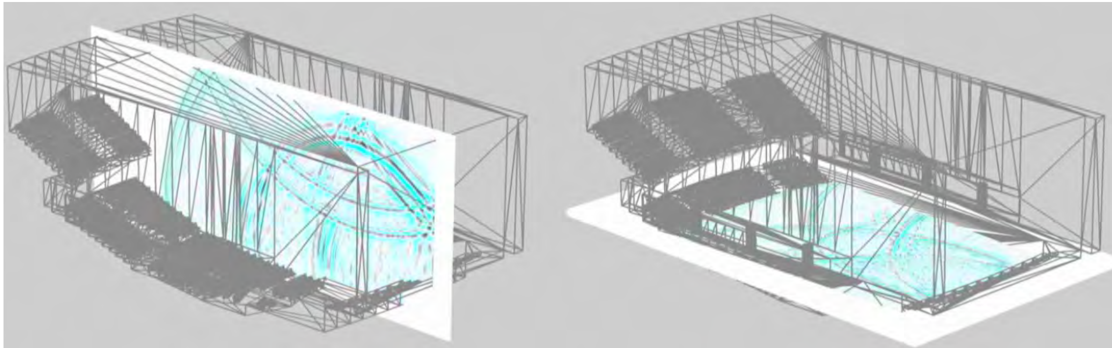

Figure 5. *Screenshot from wave-based simulation of sound propagation in the Experimental Media and Performing Arts Center Concert Hall, Troy, NY.*

proximation for asymptotically high frequencies, when the wavelength of sound is much smaller than the dimensions of room surfaces but not for low frequencies or wave behaviors such as diffusion and diffraction. Wave-based modeling requires approximating the solution to the wave equation, typically using finite volume, finite element, or boundary element methods. These methods have existed for many years, but computational complexity has limited widespread use in concert hall acoustical design. **Figure 5** shows a screenshot from a wave-based simulation, modeled as part of a research effort to highlight its potential utility in concert hall acoustics (Hochgraf, 2015). By harnessing the computing power of parallelized finite-volume simulations over multiple cloud-based graphics-processing units (GPUs), wave-based modeling may become widely available and computationally efficient very soon, allowing acousticians to test their designs with more accuracy and reliability (Hamilton and Bilbao, 2018).

An auralization will never replace the real experience of listening to music in a concert hall because it does not enable direct, engaging communication between musicians and listeners. As a musician and frequent audience member myself, I look forward to more opportunities in the future to draw from these real listening experiences and to use auralization as a research and design tool to support innovative, "excellent" design.

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BioSketch

Kelsey Hochgraf is a senior consultant in the architectural acoustics group at Acentech, Cambridge, MA. She works on a variety of interdisciplinary projects but has a particular interest in the performing arts and educational facilities as well as in acoustical modeling and auralization. Kelsey also teaches an acoustics class in the mechanical engineering department at Tufts University, Medford, MA. She holds a BSE in mechanical and aerospace engineering from Princeton University, Princeton, NJ, and an MS in architectural acoustics from Rensselaer Polytechnic Institute, Troy, NY. Find out more about Kelsey's interests and background in "Ask an Acoustician" in the winter 2017 issue of *Acoustics Today*.