Reflected Sound: Friend or Foe?

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Sound-reflective surfaces are everywhere in natural environments. Objects, walls of a room, even our own bodies are all examples of sound-reflecting surfaces. What we hear in natural environments from a source of sound is therefore a complex combination of sound that reaches our ears directly from the source and sound that has been reflected from one or more surfaces. The trouble is, what if we only are interested in the direct sound? Then reflected sound is unequivocally viewed as a contaminant. This is true for many situations, from measurements of loudspeaker responses to understanding speech in natural environments. In other situations, however, reflected sound can provide valuable information about the listening environment that can enhance sound quality and improve abilities to localize the sound source. The purpose of this article is to discuss the many ways in which reflected sound contributes to our listening experiences, both positive and negative. Although the focus is largely on humans listening in air, many of the topics discussed have parallels in other species and through other media.

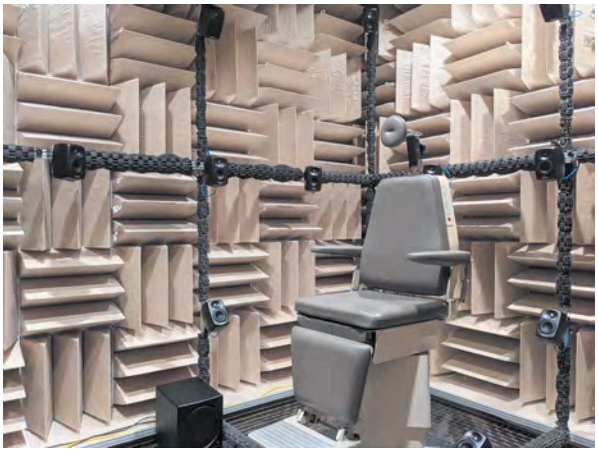
Reflected Sound Contaminates Acoustical Measurements

Let's begin by examining an example of the physical effects of reflected sound. Consider a situation in which a microphone is used to capture the acoustic energy coming directly from a loudspeaker. Along with this direct sound, the microphone will also pick up reflected sound from nearby surfaces, such as the room walls, ceiling, and floor. This fact is well-known to acousticians, and it is the rationale for the use of very specialized (and very expensive) measurement facilities known as anechoic chambers, such as the one shown in **Figure 1**.

The term "anechoic" literally means "without echo" or without any reflected sound. This, of course, is an aspirational ideal. In practice, anechoic chambers are large rectangular rooms designed to minimize both reflected sound inside the chamber and noise contamination from outside the chamber. The minimization of reflected sound is accomplished by placing large, sound-absorptive wedges on all six surfaces of the room (see Beranek and Sleeper, 1946, for original research behind anechoic chambers). The shape, material, and dimensions of the wedges determine the lower cutoff frequency at which the chamber can be considered anechoic. The chamber shown in **Figure 1** has interior dimensions of approximately 4 × 4 × 4 m and is covered in 46-cm fiberglass wedges, with a low-frequency cutoff of 190 Hz and a noise floor of <7 dB sound pressure level (SPL) from 100 Hz to 16 kHz. This chamber is currently configured with multiple loudspeakers and a height-adjustable chair for the listener (**Figure 1**).

To concretely demonstrate the contaminating effects of echoes, **Figure 2** shows a frequency-response measurement from one of the loudspeakers visible in **Figure 1**.

Figure 1. *An anechoic chamber made up of walls of fiberglass wedges to absorb nearly all acoustic energy that hits the walls. This anechoic chamber is located at the University of Louisville, Louisville, Kentucky, and was built by Eckel Industries Inc., Cambridge, Massachusetts. It is outfitted with an array of loudspeakers (36 Genelec 4420A monitors plus two subwoofers) and a chair for virtual acoustic listening tests.*



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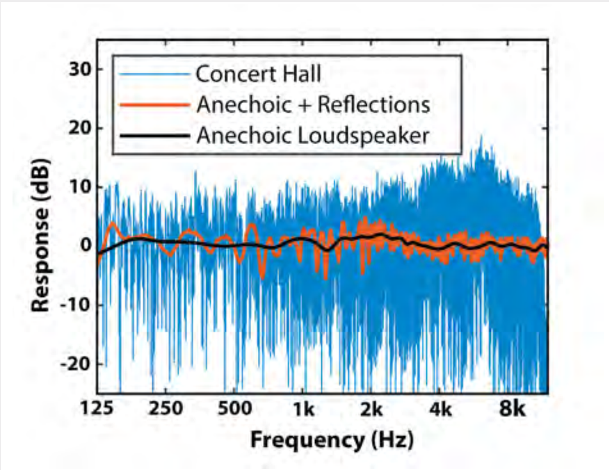


Figure 2. *Frequency responses for a large concert hall (**blue**), the direct sound and a few reflections in the anechoic chamber from **Figure 1** (**orange**), and only the direct sound from the loudspeaker in the anechoic chamber (**black**).*

The "Anechoic Loudspeaker" trace in **Figure 2** represents a measurement from 2 m, with time windowing applied to the measurement to remove any residual contributions of sound reflected from other objects in the chamber, such as other the loudspeakers or equipment.

How much could such reflected sound contaminate a measurement, given that the measurement is done within an anechoic chamber? The "Anechoic + Reflections" trace in **Figure 2** shows a raw measurement without time windowing, and ripples in the spectrum caused by acoustic reflections may clearly be observed.

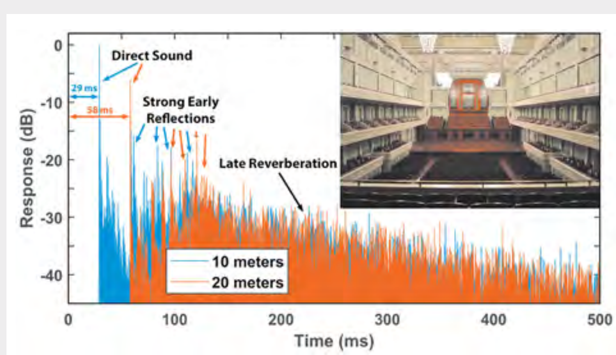
Thus, even within an anechoic chamber, reflections from equipment in the chamber can still cause significant distortions to measurements. These distortions pale in comparison to what a measurement from the same loudspeaker might look like if it is in a reverberant environment, such as a concert hall. The "Concert Hall" trace in **Figure 2** shows such a measurement at 10 m in the Laura Turner Concert Hall at the Schermerhorn Symphony Center in Nashville, Tennessee (**Figure 3,** *inset*). Severe distortions in the frequency response of the hall compared with that of a single loudspeaker are evident. Clearly, for acoustical measurements, an anechoic chamber, even if it is filled with equipment that reflects sound, is still much better than no chamber at all!

Reflected Sound is Critical for Good Concert Halls and Sound Quality

Although anechoic chambers may be good for acoustical measurements, they are terrible rooms for listening to and enjoying music. This is what concert halls are for. The sound quality benefits of listening in a concert hall can be easily and dramatically demonstrated by comparing **Multimedia File 1** (see acousticstoday.org/zahorikmedia), a passage of music recorded in an anechoic chamber, to a simulation of concert hall listening (Laura Turner Concert Hall; **Figure 3,** *inset*) for the same passage using virtual auditory space techniques (**Multimedia File 2** at acousticstoday.org/zahorikmedia). Listening through a good pair of headphones, most would agree that the concert hall simulation, with its copious amounts of reflected sound, results in much better and more natural sound quality than the sound recorded in the anechoic space. So, reflected sound, even though it can contaminate acoustical measurements, may not be so bad after all.

What is it precisely about a concert hall sound that leads to good perceived sound quality? This has been an active area of scientific research in architectural acoustics for more than 100 years (see Hochgraf, 2019, for an excellent introduction). In general, scientific research in this area seeks to relate physically measurable aspects of room acoustics to subjective attributes of the listening experience. Critical to this endeavor are good methods of room acoustical measurement and the subjectively validated metrics derived from such measurements.

Figure 3. *Laura Turner Concert Hall at the Schermerhorn Symphony Center in Nashville, Tennessee, a modern shoebox-style concert hall (**inset**). Time decay plots of the room impulse responses (RIRs) were measured 10 (**blue**) and 20 (**orange**) m from the stage (Neal, 2019).*



A basis for measurements of room acoustic metrics is the room impulse response (RIR). Any room can be accurately conceptualized as an acoustic system with both an input such as an instrument playing or person speaking, and an output such as a microphone placed in the room. An RIR is a recording of an impulsive sound, such as a hand clap or gun shot, emitted in the room, including all of the reflected sound resulting from the impulse interacting with room surfaces. **Figure 3** shows an RIR for the Laura Turner Concert Hall using an omnidirectional microphone and an omnidirectional loudspeaker source at 10 m (*blue*) and 20 m (*orange*).

The RIR has three primary components: the direct path response, early reflections, and later arriving reverberation. The direct path response occurs first in time. It contains the electroacoustic effects of the equipment in the measurement chain as well as a pure delay related to the distance between the sound source and the measurement point in the hall. In the situation shown in **Figure 3**, the pure delays for 10-m and 20-m sources were approximately 29 ms and 58 ms, respectively. Individual reflections from room surfaces occur after the direct path and are visible in **Figure 3** as "spikes" in the RIR out to approximately 100 ms beyond the direct path responses. These reflections result primarily from the hall's side walls, stage walls, balcony fronts, and ceiling. Reflections become increasingly dense at longer delays, and collectively, their levels decay in an exponential manner (linear decay in dB). This is late reverberation.

If you place an actual person where you took the measurements in the hall, additional acoustic effects are introduced, such as the contributions of the head and external ears. Measurements that include these listener-based acoustical effects are known as binaural room impulse responses (BRIRs). BRIRs not only contain additional information that is important for characterizing directional aspects of sound, including interaural level differences (ILDs) and interaural time differences (ITDs), but they also can be used to create highly realistic sounding "auralizations" of a particular room listening situation (Vorländer, 2020) that can be played back over headphones.

Although both BRIRs and RIRs represent complete physical descriptions of the acoustical characteristics of a hall, a variety of metrics have been developed in attempts to more directly relate to certain key perceptual attributes of room acoustics, such as sound clarity, reverberance, loudness, timbre, and spatial impression. Common metrics include measurements of reverberation decay time, relative levels of early-to-late energy, relative levels of direct sound to reverberation, interaural coherence or correlation, relative levels of laterally arriving sound energy, and amplitude modulation characteristics. Although many such metrics were historically measured with methods other than the RIR, nearly all can be derived from an RIR or BRIR. Details on standard metrics can be found in International Organization for Standardization ISO 3382-1, Annex A (2009), including summaries of the smallest changes in each metric that are "just noticeable." Although understanding the relationships between sound perception in concert halls and physical metrics remains an active area of study today, one thing is clear: reflected sound is necessary for good listening experiences in concert halls.

Reflected Sound and Sound Localization on the Horizontal Plane

Unlike the clear effects of reflected sound on acoustical measurements and sound quality in concert halls, reflected sound often has little effect on the abilities of listeners to localize a sound source on the horizontal plane. This remarkable insensitivity of localization to reflected sound has been shown to exist in rooms both small (Bech, 1998) and large (Hartmann, 1983), and it is thought to result from auditory processes that underlie a phenomenon known as the "precedence effect." To describe this effect, consider the following highly simplified listening scenario in which there are two loudspeakers on the horizontal plane in an anechoic space. One loudspeaker represents the sound source direct path, and the second loudspeaker represents a single ideal reflection by simply delaying the source signal in time. Such a setup allows for easy experimental manipulation of the delay (τ) between the simulated direct path and the simulated reflection.

Different sound attributes result for different values of τ. For impulsive signals at very short delays (τ < 1 ms), a single fused sound image at a location somewhere between the two loudspeakers is typically reported. This effect is known as "summing localization." At intermediate delays (1 ms < τ < 5 ms), a single sound image at the location of the direct-path loudspeaker is reported. This is the precedence effect, where the first arriving sound takes precedence in determining the perceived location. At longer delays (τ > 5 ms), the direct path and reflection are perceived as separate images at distinct spatial locations. Similar effects are also observed for longer duration signals, although greater values of τ are required to achieve similar effects.

Even though the precedence effect has most often been studied under highly simplified conditions, it offers a potential explanation for why physically measurable reflections in everyday environments are often not heard as separate auditory events. Perhaps because of this, the precedence effect has been one of the most widely studied listening phenomena related to sound perception in rooms. Although the original report on precedence focused on the spatial aspects of the effect (Wallach et al., 1949), the term "precedence effect" has come to be associated more broadly with listener sensitivity to both spatial and nonspatial aspects of reflected sound (see Brown et al., 2015, for a recent review). Current best evidence suggests that the suppression of reflected sound audibility demonstrated by the precedence effect is largely explainable by brainstem-level auditory processing, but there are aspects of the precedence effect, such as known longer term adaptations to reflected sound, that appear to involve more central brain processes.

Although the precedence effect may explain why lateral reflections within a few milliseconds of the direct path sound do not affect its apparent direction, later arriving reverberant sound can affect localization accuracy. This is because late reverberation is not directionally specific but is rather spatially diffuse. As a result, increases in reverberant energy can cause distortions to the primary acoustic cues, ILD and ITD, in the horizontal direction. Specifically, reverberation will cause the ILD to decrease and the ITD to become less reliable. Extraction of the ITD cue from ongoing signals is thought to be accomplished through analysis of the correlation between signals at the two ears. Thus, lower binaural correlation can lead to more variable, and therefore less reliable, estimates of ITD.

Figure 4 shows binaural cross-correlograms that demonstrate how the ITD cue, as estimated by the maximum value of the interaural cross-correlation (IACC) function in each frequency band, becomes less pronounced (e.g., lower magnitude and less consistent across frequency) as the acoustic complexity of the environment is increased from an anechoic space (**Figure 4A**) to a space with a single reflection (**Figure 4B**) to a reverberant room (**Figure 4C**). Because the ITD is normally a dominant cue for horizontal sound source direction, this may explain why directional localization sometimes suffers in reverberation.

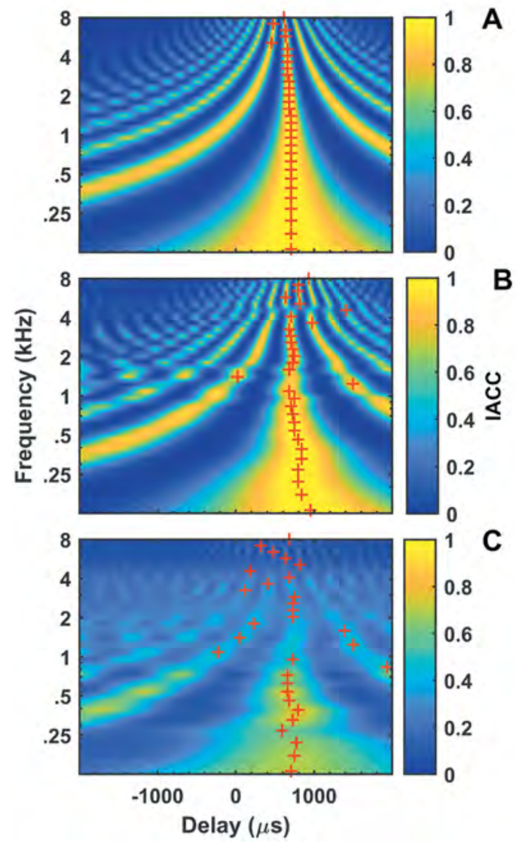


Figure 4. *Binaural cross-correlograms (contour plots of interaural cross-correlation [IACC] as a function of frequency and interaural delay) for an anechoic space (**A**), a simulated room environment with a single reflection (**B**), and a reverberant room environment (**C**). In all cases, the sound source was located at a 90° azimuth. **Red + symbols:** maximum values of IACC for each frequency channel, which represent the interaural time difference (ITD) cue to direction. Note the changes across the environment in IACC maxima and the delays at which the maxima occur.*

Reflected Sound Enables Sound Localization in the Vertical Plane

In humans, the primary acoustical cue to the vertical position of a sound source results from the directionally dependent filtering caused by the head, body, and external ears (pinnae). Major aspects of this filtering have

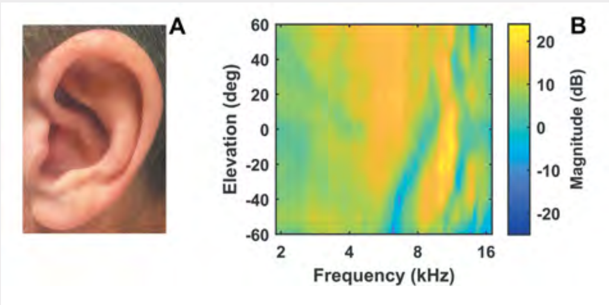


Figure 5. *Left external ear (pinna) of a participant (**A**) and the corresponding head-related transfer functions (HRTFs) as a function of sound source elevation angle (**B**). The sound source azimuth angle was –90°. Note the complex changes in spectral features of the HRTFs as elevation changes.*

been shown to result from acoustic reflections caused by aspects of the pinna structure (Wright et al., 1974) and from other parts of the body such as the shoulder (Algazi et al., 2001). These effects can be seen in head-related transfer function (HRTF) measurements. **Figure 5** shows an example of the changes to the HRTF in response to changing source elevation. Interestingly, humans have been shown to be extremely sensitive to their own HRTFs but are also able to adapt to new HRTFs (Hofman et al., 1998) through what is presumed to be a form of perceptual learning (Zahorik et al., 2006).

Reflected Sound, Distance Localization, and Externalization

Like vertical plane localization, the ability to localize sound in distance depends critically on reflected sound. For distance, however, it is not reflected sound from the listener's own body that provides localization information. It is instead sound reflected from objects in the environment. The ratio of direct (D)-to-reverberant (R) sound energy (D/R) is a primary cue to sound source distance, and it has two important properties. It systematically decreases as source distance increases and is independent of the acoustic power of the source.

Figure 3 shows examples of these two properties in the RIRs from the concert hall shown in **Figure 3,** *inset*. Moving from a 10-m source distance to a 20-m source distance at a constant source power causes the level of the direct-path to decrease by approximately 6 dB (consistent with the inverse-square law), but the level of the late reverberant sound remains nearly the same anywhere in the room. This results in systematic decreases in the D/R with increasing distance as well as the D/R being independent of source power. Human auditory distance perception is known to be critically dependent on the D/R because it is dramatically disrupted when no reflected sound is present, such as in anechoic listening environments (see Kolarik et al., 2016, for a review). It is also negatively affected by hearing loss.

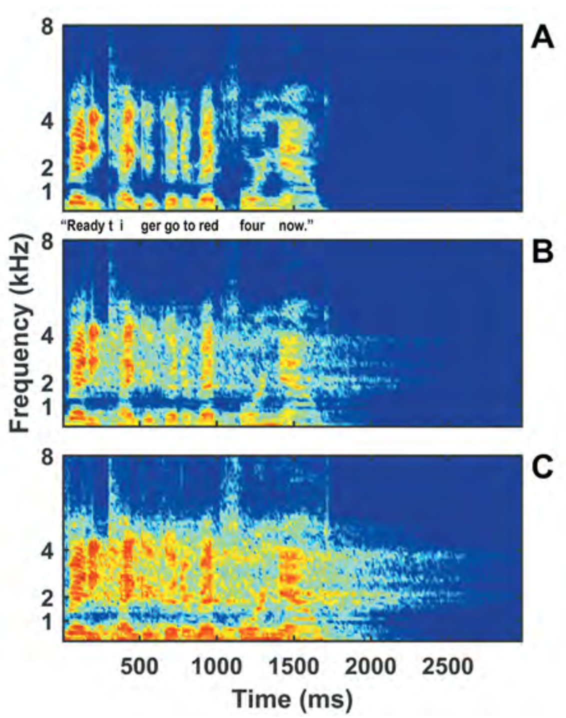
Reverberant sound also has another important perceptual role. It can help support the perception that a source of sound is spatially external to the listener's head. This issue of externalization is critical for sound reproduction over headphones, where in the absence of any additional processing, sound is typically not externalized. Although reverberation is thought to have a major impact on externalization, there are also additional factors that contribute, such as head movement, binaural information, the spectral details related to a listener's own HRTFs, visual information, and cognitive factors such as expectation (see Best et al., 2020, for a review). Currently, there is no clear consensus as to how externalization may or may not be related to distance perception and whether externalization is categorical or continuous in nature. Nevertheless, externalization has clear practical importance for realistic sound reproduction over headphones, particularly regarding implementation of virtual auditory space techniques. Sound externalization is also known to be negatively affected by hearing loss, and listening with devices commonly used to treat hearing loss, such as hearing aids or cochlear implants (CIs), often result in perceptions of nonexternalized sound.

Reflected Sound and Speech Understanding

Speech understanding and speech perception have long been known to be impacted by room acoustics and reflected sound. In general, reflected sound is thought to degrade speech understanding, but the degradation is caused primarily by late reverberation. Surprisingly, early reflections often have little impact on speech perception (Haas, 1972) due to the precedence effect, and they can even enhance speech understanding and clarity. Such benefits of early reflections are thought to be explainable based on temporal integration of the energy from early reflections with energy from the direct-path, which results in an effective amplification of direct-path sound (Bradley et al., 2003). Room reverberation, however, causes multiple degradations to the speech signal that can impair speech understanding.

The primary degradation caused by reverberation to the speech signal is temporal in nature. For example, **Figure 6A** displays a spectrogram of a speech sentence in an anechoic space. The color temperature indicates the level of the speech. Regions of high level correspond to syllables and words in the sentence. In the anechoic space, words in particular tend to be surrounded in time by regions of silence (**Figure 6A**). In a strongly reverberant room (**Figure 6B**), the reverberation fills in the silent periods between words, resulting in temporal "smearing" of the speech signal where the amplitude variations or modulations as a function of time become much less prominent. This reduction in the amplitude modulation (AM) characteristics of the speech signal forms the basis for a widely used and successful method of predicting speech understanding in both reverberant and noisy listening environments, the Speech Transmission Index (STI) (Steeneken and Houtgast, 1980). Temporal masking phenomena also contribute to aspects of decreased speech understanding in reverberation because reverberant energy from preceding speech can mask speech sounds that follow.

Figure 6. *Spectrograms of the sentence "Ready tiger go to red four now" spoken by a female talker (Bolia et al., 2000) in (**A**) anechoic space, (**B**) a reverberant room, and (**C**) the same reverberant room as in **B**, but after application of fast-acting wide dynamic range compression similar to that found in modern hearing aids (compression parameters based on Reinhart et al., 2019). Color temperature indicates relative sound level.*



There are at least three phenomena that appear to somewhat counteract the temporal degradations to speech caused by reverberation and may explain why speech communication is relatively unaffected in many reverberant environments. One is the known benefit of listening with two ears. This binaural advantage likely relates to more general aspects of binaural processing, such as a known "binaural squelch" of reverberation (Koenig, 1950) and effects related to the binaural masking level difference (Licklider, 1948).

A second is the known benefit of spatial separation between the speech target and competing sources of noise that mask the speech target. This benefit is often referred to as a spatial release from masking (SRM). The SRM can improve speech reception thresholds by as much as 18 dB in an anechoic space. However, the effects are generally much smaller in reverberation (Marrone et al., 2008). This is likely due to distortions to the ILD and ITD cues caused by reverberation and the resulting decreases in the precision with which the directions of target speech and competing sound sources can be localized.

A third remarkable phenomenon that can functionally decrease the negative effects of reverberation on speech understanding relates to demonstrated abilities of humans to adapt to reverberant listening environments. For example, brief periods of exposure (of just a few seconds) to moderately reverberant rooms have been shown to increase word intelligibility by up to 20% (Zahorik and Brandewie, 2016). Similar adaptation effects have been demonstrated across a range of different listening tasks.

Two listener factors that may negatively impact speech understanding in reverberation are hearing impairment and age. In adults, there is consensus that both factors are related to poor speech understanding in reverberation. However, it is difficult to assess the independent contributions of each factor, given the strong natural association between hearing impairment and ageing. In an important study where samples of listeners were intentionally chosen to isolate the effects of age from hearing impairment, both factors were found to independently contribute to poorer speech understanding in reverberation (Helfer and Wilber, 1990). In children, the effects of age are reversed. Speech understanding performance improvements have been shown to follow a progression of developmental improvement (Neuman et al., 2010), which may have particularly important implications for the acoustical design of classrooms.

Adding to the potential challenges resulting from hearing impairment, common strategies for the treatment of hearing impairment are not entirely effective in the presence of reverberation. One reason for this is that reverberation can decrease the benefit of certain processing strategies commonly used in hearing aids (Reinhart and Souza, 2016). such as fast-acting wide dynamic range compression (WDRC). An example of this is shown in **Figure 6C** where WDRC can be seen to further amplify the effects of reverberation. Although directional microphones can mitigate some of these problems, there is evidence that hearing aid users are keenly aware of the challenges posed by reverberation because it appears as one of the most frequent complaints on a widely used self-report scale of hearing aid benefit (Johnson et al., 2010). Reverberation is also known to be a major problem for CI users, given that the success of CI devices depends largely on good temporal coding of the speech signal and reverberation distorts this temporal coding.

Reflected Sound in Natural Environments

What about environments other than anechoic chambers and concert halls? We argue that most natural environments are much more like the latter than the former, given the ubiquity of sound-reflective surfaces in the natural world. Even a snow-covered outdoor environment produces audible reflected sound in response to a hand clap (**Multimedia File 3** at acousticstoday.org/zahorikmedia) compared with the sound an anechoic chamber (**Multimedia File 4** at acousticstoday.org/zahorikmedia). Some of the more reflective natural environments, such as a tunnel (**Multimedia File 5** at acousticstoday.org/zahorikmedia) or a cave, can have qualities not dissimilar to those in concert halls (**Multimedia File 6** at acousticstoday.org/zahorikmedia).

Thus, what is learned in the study of reflected sound in an enclosed space or under simplified sound-reflective conditions likely has applications to many listening situations in natural environments and for other species. For example, similar to humans, songbirds are known to use the D/R cue to judge distance in their natural habitats (Naguib, 1995), and many species rely on the directionally dependent filtering of the external ear to encode an auditory space, even those that do so via active echolocation, such as bats (Aytekin et al., 2004). Reflected sound is also not limited to listening environments in air. Underwater soundscapes, too, can have significant contributions from reflected sound (Miksis-Olds et al., 2018).

Conclusions

Reflected sound, from the environment and from ourselves, is pervasive. Although its physical effects are undeniable, the impact on our listening experiences are varied. On one hand, reflected sound is critical for sound sources to be externalized and localized in distance and elevation. It enhances sound quality, such as that experienced in a concert hall, and early reflections can improve speech understanding. On the other hand, strong reverberation can degrade directional sound localization and has a major impact on speech understanding, particularly for individuals with hearing impairment. However, more moderate amounts of reflected sound often have relatively little impact on our listening experiences. Aspects such as binaural hearing, adaptation, and precedence all appear to facilitate suppression of reflected sound within the auditory system. More research is needed to fully understand the perceptual effects of reflected sound, particularly because most research on human hearing has been conducted in listening situations specifically designed to minimize reflected sound's physical effects. Anechoic chambers or headphones are great for this purpose, but these are not the listening situations in which we spend most of our time and certainly are not the situations in which the auditory system has evolved. Whether or not reflected sound is considered a friend or a foe, one thing is for sure: it is here to stay.

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