Acoustics Today

Spring 2024 Volume 20, Issue 1

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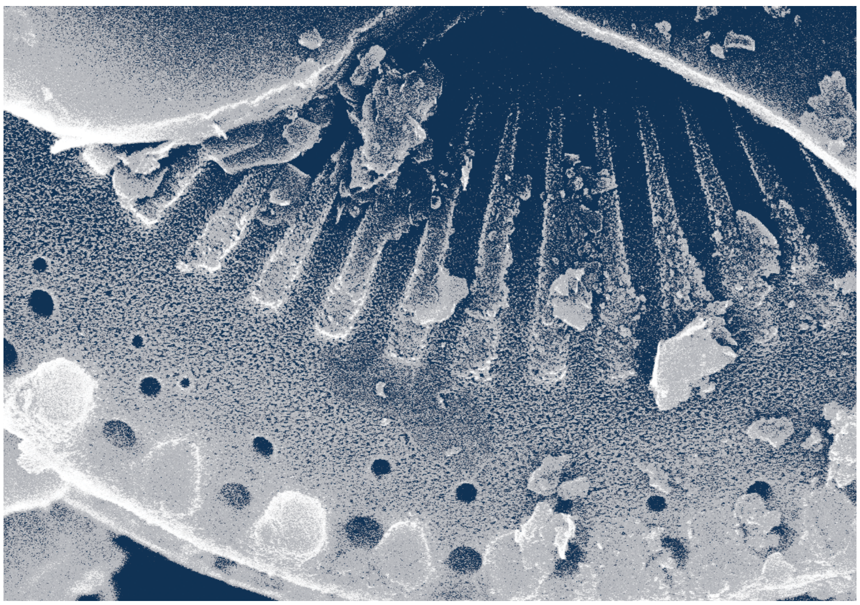

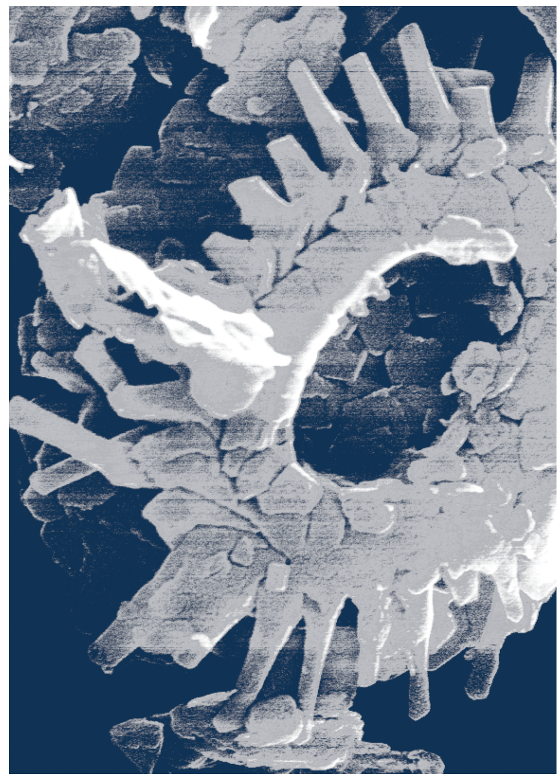

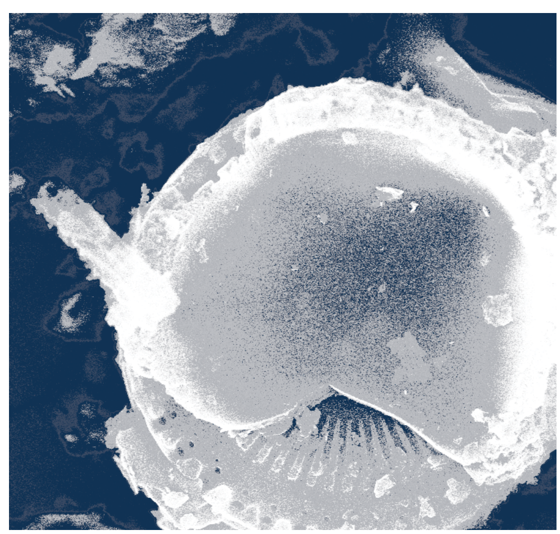

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Images of mud from the New England Mud Patch, from the article "Mud Acoustics" by Charles W. Holland, Stan E. Dosso, and Jason D. Chaytor (page 37). Images are adapted from Dubin, J. T., Venegas, G. R., Ballard, M. S., Lee, K. M., and Wilson, P.S. (2017). "Physical and acoustical properties of marine sediments containing a wide particle size distribution." *Proceedings of Meetings on Acoustics* 31(1), 070001, with permission of Acoustical Society of America.

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From the Editor

Arthur N. Popper

This is my last year as editor of *Acoustics Today* (*AT*). I'll write more about my "retirement" in the winter issue, but I wanted to mention my stepping down because the Acoustical Society of America (ASA) is conducting a search for the next editor and I would like to encourage readers to consider applying. The application deadline is March 15, 2024. Although most of you have hopefully learned about the position when it was first advertised in December, just in case you missed the advertisement, see acousticalsociety.org/editor-acoustics-today.

The only thing I will add is that being editor of *AT* has been one of the most interesting and enjoyable positions I've held over my career, and I trust that other ASA members would equally enjoy being *AT* editor. Indeed, being editor of *AT* has enabled me to make what I think is a unique, and hopefully valuable, contribution to the ASA.

What has been particularly exciting about being editor is that I have had the opportunity to learn an immense amount about diverse areas of acoustics, gotten to meet and know a wonderful group of interesting people, and had a grand time helping educate all of us about the amazing diversity of acoustics. And, I have had the honor of working with a truly grand set of people in ASA Publications. They contribute greatly to making *AT* the quality magazine that it is, and they make the job of editor relatively easy.

Finally, as we look for a new *AT* editor, there will be an additional change starting in 2025. *AT* will be published two, not four, times each year. The magazine will still be delivered to every ASA member and be on the web for members and our many other readers. Most important, the ASA is committed to ensuring that the quality of our content will continue to be of immense interest and value to help our readers learn about the amazing breadth of our discipline.

Now, on to the spring 2024 issue of *AT*! This issue, like all the others I have edited, contains a pretty diverse range of topics. The first article is by David R. Barclay, who discusses passive sensing of sounds in the ocean. David shares how, using modern technology, it is possible to learn an immense amount, not just about things in the ocean but also about things that go on in the oceans such as ocean structure, the seabed, and the physical properties of seawater.

Our second and third articles focus on the soundscape during COVID-19 and its consequences. These articles differ in their approaches but reach comparable conclusions related to soundscape changes and societal challenges. In this common context, the importance of soundscape research in supporting the quality of life in urban areas becomes particularly clear.

Our second article is by André Fiebig and Brigitte Schulte-Fortkamp. André and Brigitte have been pioneers in soundscape research and they extend the topic to consider how soundscapes changed during and after COVID. One of the many issues they consider is whether with the changes in society after COVID, the soundscape will return to its pre-COVID characteristics.

In our third article, Yoshimi Hasegawa and Siu-Kit Lau consider soundscape changes during the pandemic. One of the many fascinating things considered by Yoshimi and Siu-Kit is the acoustic changes that occurred during COVID and how humans perceived the changes in the soundscape.

The fourth article returns to the oceans but from the perspective of mud! The authors, Charles W. Holland, Stan E. Dosso, and Jason D. Chaytor, take mud, something most of us were "expert" at as kids, and show how it plays a critical role in the oceans. In their article, the authors consider the nature of mud and its properties and discuss how investigators use acoustics to understand the nature of mud and the oceans.

Continued on Page 10...

From the President

Stan Dosso

Acoustics 2023 Sydney

I am writing this column shortly after returning home from the Acoustics 2023 Sydney meeting held December 4-8, 2023, in Sydney, New South Wales, Australia. This was a joint meeting that comprised the 185th meeting of the Acoustical Society of America (ASA) and the 2023 meeting of the Australian Acoustical Society (AAS) as well as the Western Pacific Acoustics Conference (WESPAC) and the Pacific Rim Underwater Acoustics Conference (PRUAC). This meeting represented a major event for the ASA, for acoustics in the Western Pacific in general, and was the culmination of years of planning and preparation on both sides of the Pacific. Hence, I thought I would devote this column to the Sydney meeting and to some future joint ASA meetings.

Acoustics 2023 Sydney was held at the state-of-the-art Sydney International Conference Centre (ICC), which provided first-rate facilities and a spectacular setting on Darling Harbour, within the larger Sydney Harbour, with the major conference hotels within a few minutes walk. The city of Sydney has done a wonderful job developing its harbors for public accessibility and enjoyment, and you can walk (I did) from the ICC along the waterfront past restaurants, shops, parks, skyscrapers, and working quays and under the famous Sydney Harbour Bridge to the iconic Sydney Opera House and Royal Botanic Gardens in about 45 minutes. Alternatively, Sydney ferries act as a city marine-bus system, efficiently and scenically connecting many points around Sydney Harbour and its islands (I took the ferry ride back from my walk). Sydney proved to be a fabulous locale for the meeting, as our Australian hosts had promised, and it didn't hurt that it was summer (in December) there!

The meeting itself consisted of about 1,150 presentations and 210 posters organized into 127 technical sessions, including 60 special sessions, plus 2 superb keynote talks: Andone Lavery from the United States on "Exploring the Ocean with Sound: Telltale Acoustic Signatures of a Changing Ocean," and Cath McMahon from Australia on "The Listening Brain's Response to Adversity." In all, there was a total of about 1,420 attendees from 41 countries (summarized in **Table 1**). This represents the largest ASA meeting attendance since our joint meeting with the European Acoustical Association (EAA) in Boston in 2017, and although United States attendance was somewhat lower than at a typical domestic meeting, strong participation from Australia and other Pacific Rim countries made for a very successful international meeting. In particular, the conference provided an opportunity for Western Pacific acousticians who cannot easily travel to the United States to attend an ASA meeting closer to home, potentially leading to further engagement with the ASA in the future.

The meeting included a large exhibition with 50 participating companies who sponsored an opening night welcome reception. A buffet social featuring excellent local cuisine was also held on Wednesday evening. Conference technical tours were organized to the Australian Hearing Hub (see hearinghub.edu.au) and other world-class facilities, including Cochlear at Macquarie University (see cochlear.com/au/en/home) and the Sydney Opera House (see sydneyoperahouse.com). The musical JAM session was particularly noteworthy, with 200+ people filling the venue and an unplanned drop-in performance by David McKenzie, one of Australia's renowned Ten Tenors. Meeting trivia (provided by AAS President Jeff Parnell) included that $10,000 worth of Barista Coffee, 5 kilograms of popcorn, and 20 liters of ice cream were served at refreshment breaks during the meeting.

The ASA supported the travel of about 160 participants to attend the meeting, including students and early-career acousticians from various ASA programs. This included the Down Under Funder, which raised $1,000 travel grants for 100+ North American acoustics students based on contributions from the ASA technical committees (TCs) over the past few years.

TC reports on the Sydney meeting made to the ASA Technical Council at the conclusion of the meeting were overwhelmingly favorable in virtually all aspects and

Table 1. *Acoustics 2023 Sydney attendance by country*

Country	Attendees	Country	Attendees	Country	Attendees
Australia	512	Poland	7	Benin	1
United States	386	Indonesia	6	Brazil	1
China/Taiwan	119	Switzerland	5	Chile	1
South Korea	91	Austria	3	Ghana	1
Japan	86	Denmark	3	Iceland	1
Canada	35	Mexico	3	Iran	1
Germany	31	Sweden	3	Israel	1
New Zealand	29	Belgium	2	Moldovia	1
United Kingdom	25	Saudi Arabia	2	Peru	1
India	14	Spain	2	South Africa	1
Singapore	11	Sri Lanka	2	Thailand	1
France	9	Algeria	1	United Arab Emirates	1
Italy	8	Argentina	1	Viet Nam	1
Netherlands	8	Bangladesh	1		

reflect my own personal experience of excellent technical content, a well-organized conference, enjoyable social programs, and a memorable time in Australia.

Of course, planning and running a diverse international meeting such as this represents a huge undertaking. The idea of holding a joint meeting in Sydney was initiated in 2017 by Brian Ferguson of the AAS, who is also an ASA Fellow. To judge interest in such a meeting, Brian took the idea to each of the (then) 13 ASA TCs. Each TC held a vote and all but one approved the idea of a joint Sydney meeting, with one TC vote resulting in a tie. Given this strong support, ASA Executive Director Susan Fox asked Marcia Isakson to represent the ASA as cochair of the meeting and work with AAS Cochair Jeff Parnell. James Miller was recruited as the ASA technical cochair to work with the AAS counterpart Benjamin Halkon. WESPAC and PRUAC also joined as cohosts of the meeting, in keeping with the Pacific setting.

The joint meeting was originally planned for Fall 2021, but the COVID-19 pandemic intervened and forced the ASA and AAS to make the difficult (but correct) decision to postpone the meeting two years until 2023. Although there was some concern that this delay and postpandemic travel issues might negatively affect participation, this turned out not to be the case, with the strong attendance mentioned above.

In addition to the cochairs and technical cochairs, ASA/AAS Treasurers Judy Dubno/John Wasserman and Student Reps Brijonnay Madrigal/Adrian Morris, together with Susan Fox and Elaine Moran of ASA headquarters, put in extraordinary efforts to bring the Acoustics 2023 Sydney joint meeting to successful fruition. Thanks very much to all!

Although the 2023 Fall ASA meeting represented our first joint meeting with the AAS, the ASA holds joint meetings with other acoustics societies and organizations on a fairly regular basis. For example, the ASA has held joint meetings with the EAA in Berlin (1999), Paris (2008), and Boston (2017) and plans to hold another joint meeting with the EAA in Spring 2027 at a European location to be determined soon. Likewise, the ASA has held joint meetings with the Acoustical Society of Japan (ASJ) in Honolulu (2006, 2016) and will hold another joint meeting with the ASJ December 1-5, 2025, again in Honolulu. The ASA has also held joint meetings with the International Congress on Acoustics (ICA) in Seattle (1998) and Montreal (2013) and will hold another joint meeting with the ICA May 19-23, 2025, in New

Orleans. Finally, the ASA has held joint meetings with the Canadian Acoustical Association (CAA) in Ottawa (1993), Vancouver (2005), Montreal (2013), and Victoria (2018), and we will hold our next meeting jointly with the CAA in Ottawa May 13-17, 2024. As a Canadian and member and past president of the CAA, I look forward to welcoming the ASA to Canada's national capital, which is truly beautiful in the spring.

In the big picture, periodic joint and/or international meetings provide opportunities for the ASA to more broadly carry out its mission "to generate, disseminate, and promote the knowledge and practical applications of acoustics." Such meetings can expose ASA members to new ideas, approaches, and applications in acoustics in other countries; broaden our experience and perspective; and enhance collaborations and progress across the globe. Of course, these are mutual benefits, with all the participating countries/organizations profiting in a win-win process for acoustics.

As always, I welcome your feedback (sdosso@uvic.ca).

From the Editor, Continued from Page 7

In our fifth article, Cynthia F. Moss and Laura N. Kloepper discuss the career of a truly eminent member of ASA, James Simmons. Jim, as many readers know, has spent the past 55 or more years trying to understand the bioacoustics of bats. In their article, Cynthia and Laura highlight just a few of Jim's amazing contributions, starting with his pioneering studies that involved training bats to tell him what they hear and how they echolocate. Jim continues his work even today, and he discussed some of the work in a recent issue of *AT* (see bit.ly/AT-Simmons).

Our last article is one in a series I have informally had on the architectural acoustics of various spaces. In this issue, Gary W. Siebein, Keely Siebein, Jack Wrightson, Joe Solway, and Raj Patel, talk about the acoustics of VERY large spaces such as those holding tens of thousands of people for sporting and other events. Gary and colleagues show that the acoustics in such spaces are very different than in smaller spaces or from spaces that focus on a single type of event, such as music. See related articles at bit.ly/AT-BuiltSpaces.

We have three "Sound Perspectives" (SP) essays. In our first, our "Conversation with a Colleague" (CwC) series, we meet Karl Grosh. Karl is a biomedical engineer who works on transducers. As readers will see, his interests are broad, but Karl has a particular interest in understanding the fundamental structure-function relationships in the mammalian cochlea by building mechanistic mathematical models.

In our next SP, Andy W. L. Chung and Adrian KC Lee discuss acoustics research in Asia. They discuss such research in various countries by highlighting the work of a few outstanding researchers. This essay comes out of the work of the ASA International Liaison Committee (ILC). Indeed, I was not aware of this committee, and so I found this an interesting essay and one that taught me a great deal.

Our final essay comes from the ASA Student Council and is by graduate student Marissa L. Garcia. Marissa focuses on the topic of inclusion in acoustics. She does this by sharing short essays about five young ASA members who, through their work, incorporate inclusion in various ways.

Passive Acoustic Sensing of the Ocean

David R. Barclay

Introduction

What can we learn by listening to the ocean? The ocean contains a myriad of sounds, both natural and human-made, and methods to scientifically extract information about the ocean and what is occurring within it using the sounds have made exciting advances in recent decades. Most dramatically, our abilities have progressed from listening to what is happening to the ocean (e.g., wind blowing and rain falling on the surface) to actually listening to the structure of the ocean and seabed and the physical properties of seawater itself (e.g., temperature, salinity, and pH). This article highlights some of the ways acoustical oceanographers use underwater ambient sound to measure the complex internal structure of the ocean just by listening.

Sound for Detection

Since the sinking of the Titanic in 1912 and the threat of submarine warfare starting in World War I (Manstan, 2022), sending pulses of underwater sound to find icebergs or U-boats has been the primary method for sensing in the ocean. As a result, underwater sound became and remains the mainstay of finding and mapping objects in the sea through a multitude of increasingly clever flavors of active sonar (*so*und, *na*vigation, and *r*anging) devices.

Similarly, the detection, localization, and classification of human machines and sound-producing animals using passive (silent) sonar systems has advanced to the development of listening arrays capable of surveilling the entire Atlantic or Pacific Ocean (Nishimura, 1994). As both types of sonar became increasingly sophisticated, some attention was eventually paid to characterizing the background sounds present in passive and active sonar measurements. As is often the case in scientific and engineering pursuits, this seemingly minor task, minimizing the effect of ambient noise on remote sensing *in* the ocean, resulted in the creation of a new discipline altogether, a method for sensing *of* the ocean, acoustical oceanography.

Passive Sensing in the Ocean

When we listen to the background sound in the ocean, ignoring the identifiable, attributable, and transient signals, we primarily hear what is occurring at the boundaries, the sea surface or seabed. The remote sensing of widely distributed physical processes by their random, noise-like (stochastic) acoustic signals has been a fruitful field of study since the days of Knudsen et al. (1948) and Wenz (1962). Using the power spectrum captured with just a few seconds of recording and some knowledge of the local conditions, the acoustic signatures of mechanical actions and the forces that cause them can be resolved. The frequency content can reveal the height of breaking waves at the ocean's surface (Felizardo and Melville, 1995), the microseism wave field generated by the oscillating pressure of ocean waves (listen bit.ly/47zqqiR) (Kibblewhite and Wu, 1989), the wind speed (Vagle et al., 1990), and the relative direction of the wind and surface currents (Robinson, 2020). The collective sound of rain drops give up their size, fall rate, and even their interaction with the wind and waves (listen bit.ly/3Rj8ZNA) (Ma et al., 2022). Snowflakes landing on the sea surface can produce a sound that tells the story of the atmospheric conditions under which they formed (listen bit.ly/3Gpxgvc) (Alsarayreh and Zedel, 2011). At high latitudes, the sea ice freeze up and break up provide an overture and finale to winter (Cook et al., 2022). In the darkness, the cracking sounds on the ice cover provide indications of temperature changes (listen bit.ly/3N673FG), whereas the saltation noise of snow skipping over the surface can be linked to the wind speed (Ganton and Milne, 1965). In the pack ice, wind and tidal current forcings make fragments of ice collide and rub with a predictable regularity (listen bit.ly/3N7SCRy). The sound of sediment being transported by currents flowing along the seabed can be used to estimate the grain size and the speed of the flow (Thorne, 1990). Characterizing the sounds of glaciers where they meet the sea has seen rapid progress toward the quantification of processes like calving and melting (listen bit.ly/3uDKTUW) (Deane et al., 2019).

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The acoustic signatures of hydrothermal vents reveal their presence (listen bit.ly/3RmgR0U), although the physical meanings of the sounds they generate are still to be determined (Smith and Barclay, 2022).

All these methods for extracting information about the activity of the natural world from underwater ambient sound with just a single, stationary hydrophone (underwater microphone) offer the potential to improve and inform the study of the ocean, weather, and climate. The measurement of wave-breaking statistics over large areas of the sea surface tell us about air-sea gas exchange and the ocean's ability to suck up CO_2. Quantifying precipitation on the ocean's surface is needed to understand the exchange of heat and momentum between the air and the sea as well as the mixing in the upper layers of the ocean (Laxague and Zappa, 2020). Ice coverage and freeze up and break up times in the dark and often overcast Arctic are important processes to track to improve our understanding of the changing climate at high latitudes. The presence and nature of wind, waves, rain, snow, and ice at the ocean's surface are all pragmatically monitored by sound on subsurface hydrophones.

Similarly, measuring the transport of sediments using passive acoustics avoids many biases introduced by bottom-mounted mechanical measurement devices and provides information needed to understand the stability of riverbeds, beaches, and the seafloor. Measurements of the melting and calving of glaciers, crucial to our understanding of the earth's future climate, can be made at safe distances from the unstable glacier terminus, where collapsing walls of ice can produce deadly tsunamis. The ability to determine any property of a hydrothermal vent without having to stick a sensor into its caustic, high-temperature fluid could enhance our ability to monitor these structures and their flow over long time scales and understand their contribution to the ocean's chemical cycles.

Passive Sensing of the Ocean

However, the most exciting advances in recent acoustical oceanography have combined contemporary knowledge of wave physics and methods in signal processing with innovation in ocean technology. Using massive passive acoustic datasets collected using permanent underwater listening stations connected to the shore by underwater cables, moorings tethered to seafloor, buoys floating on the sea surface, and autonomous underwater vehicles carrying arrays of hydrophones, researchers have uncovered details about the ocean's composition encoded in the background sound field. This article explores some of the answers to the question "What can we learn about the structure of the ocean and its internal properties by simply listening?" The new methods in passive-acoustic remote sensing described here can track the layering of water masses in the ocean, map the seafloor and subbottom, and solve questions related to climate change, the carbon cycle, and ecosystem health.

Noise Modeling and the Advent of Acoustical Oceanography

Applied problems, such as the detection of surface ships and submarines, are the staple of underwater acoustics. To aid in the design of optimal underwater arrays for this detection, two researchers at the US Navy Underwater Sound Laboratory, Cron and Sherman (1962), developed a basic model for the directionality and spatial correlation (statistical measure of similarity between measurements taken at two points) of underwater noise. Here, noise is defined from the opening sentence of Urick's seminal work (1984) on the subject *Ambient Noise in the Sea*, "Noise is unwanted sound." Cron and Sherman's (1962) version of the ocean was simplified to have no change in sound speed with depth, no bottom, and a smooth, perfectly reflecting sea surface. Breaking waves were modeled as totally uncorrelated sound sources, uniformly distributed across the infinitely large sea surface, collectively generating an unchanging, stationary noise. Despite these simplifications, the model predictions were found to agree very well with observations at any depth in the deep ocean (Barclay and Buckingham, 2013).

A more sophisticated physics-based model appeared a few decades later that could predict the spatial correlation of wind-driven wave noise in an ocean with a realistic bottom and sound speed profile (Kuperman and Ingenito, 1980). The expression was used to predict the performance of sonar localization algorithms that used realistic depictions of the ocean environment.

Both the Cron-Sherman (1962) and the Kuperman-Ingenito (1980) noise models treated breaking waves as uncorrelated sound sources spread across the entirety of the ocean's surface, radiating sound into the ocean below. It was noticed that this was analogous to the blue sky above, an infinite sheet of uniformly distributed uncorrelated sources of light (sunlight scattered by particles in the atmosphere), illuminating everything below.

Inspired by this analogy between ocean noise and daylight, a system to "see" underwater was built, the Acoustic Daylight Ocean Noise Imaging System (ADONIS). It consisted of a large spherical dish that reflected sound onto a dense elliptical billboard array placed at its focal point (**Figure 1**). Once placed underwater, the system made use of the ambient noise in the ocean to produce two-dimensional images of objects in the ocean, acting like an acoustic camera. When the dish was pointed in the direction of an object such as a 55-gal drum, ADONIS was capable of capturing the effect of the drum's shape, position, and composition effect on the noise field. By visualizing this acoustic information on a screen, an image of the scene was created. For example, when the 55-gal drum was placed on the seafloor, ADONIS captured images at a rate of 25 images/s, which was fast enough to create a smooth moving picture (or video) of objects within "view" of the giant dish (Buckingham, 1999).

Figure 1. *Acoustic Daylight Ocean Noise Imaging System (ADONIS) on the Scripps Institution of Oceanography Point Loma wharf, La Jolla, California. When placed in the ocean, the* ***black spherical dish*** *with a diameter of 3 m reflects and focuses underwater background noise onto the planar array of hydrophones (****yellow disc****). The dish and the array work together to create a spatial map of the noise field, arriving at the dish from different angels. This acoustic information is combined and visualized on a screen to produce images of objects in the ocean. Photo courtesy of the Buckingham Laboratory, used with permission.*

Reflections from the Seabed

During the development of the analogy of ocean surface sound as daylight, a series of experiments showed that the reflection of breaking-wave-generated ambient sound off the seabed could be used to infer geoacoustic properties. It was first shown that the measured vertical directionality of the ambient sound could be used to determine the angles at which perfect (total internal) reflection of acoustic energy did and did not occur (Buckingham and Jones, 1987). The critical angle, the largest grazing angle (angle relative to the horizontal) where total internal reflection does occur, is easily related to the acoustic impedance (sound speed and density) in the seabed.

Thus, just by listening to the directionality of background sound, one can determine the seabed acoustic properties. This technique was improved by increasing model complexity, first with analytical models that considered the seabed as an infinite extent of fluid (Deane et al., 1997), then as an elastic layer over a subbottom (Carbone et al., 1998). More recently, the theory was extended to determine the composition and thickness of the New England Mud Patch, an anomalous region of the seabed south of Martha's Vineyard, Massachusetts, where a 12–m-thick layer of mud has accumulated over the last 10,000 years. The mud has a sound speed slower than water, thus no critical angle, but the method of relating the noise directionality to seabed properties still holds (Barclay et al., 2019).

Meanwhile, an analogous theory of surface-generated ambient sound using rays in the place of waves was in development (Harrison, 1996). Application of the theory to estimate the reflection properties of the bottom was successful, using a string of vertical hydrophones in an array to measure the noise directionality (Harrison and Simons, 2002). However, the ingenious finding from the work was that the distance from the array to the seabed could also be measured. A conventional depth sounder generates a sound signal, then measures the time of flight to the seabed and back to determine the distance traveled. By the new method, the background noise is used in place of the signal by some clever signal processing on

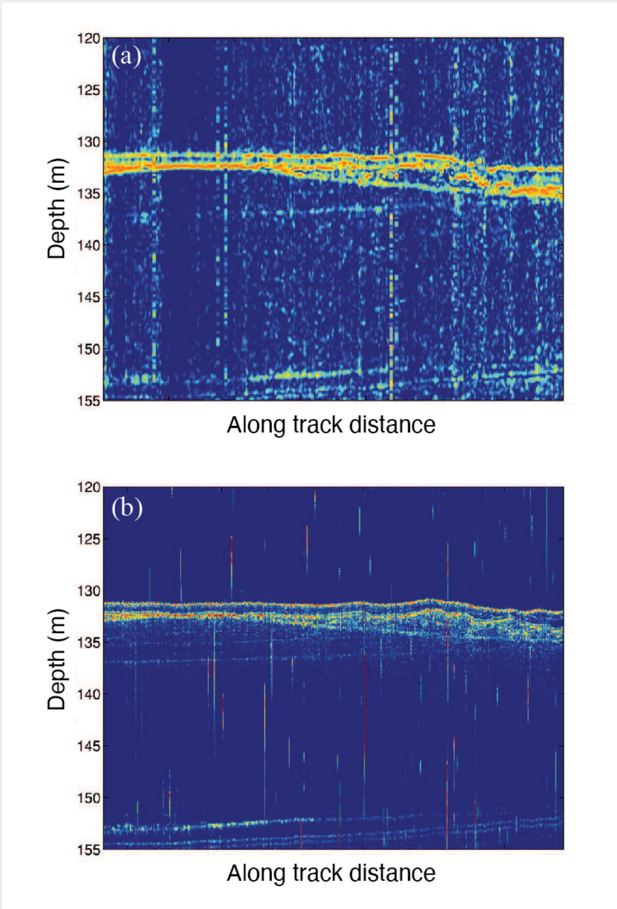

Figure 2. *The measured depth of the seabed and subbottom layers over a section of the seafloor.* ***Color scale:*** *intensity of the acoustic return (**red** is high; **blue** is low).* ***a:*** *Produced using ambient-noise fathometer processing applied to a drifting vertical hydrophone array.* ***b:*** *Made using a ship-towed active sonar used for seismic surveys. The two measurements were made over approximately the same segment of the seafloor, where the ship's track followed that of the drifter. The **vertical axis** is two-way travel times converted to depths using 1,500 m/s sound speed and the **color scale** covers 12 dB in dynamic range. Adapted from Siderius et al. (2006).*

the data from the vertical array. This technique of depth sounding with ambient noise turned the drifting array into a passive fathometer, capable of mapping the ocean bottom and its subbottom structure without putting any new sound into the environment (**Figure 2a**) (Siderius et al., 2006). For comparison, a very loud active sonar normally used for seismic surveys was towed behind the ship and used to measure the bathymetry along the same drift track as the passive fathometer (**Figure 2b**).

The idea of using noise to determine the position and properties of the seabed was pushed further to acoustically monitor the health of grasses growing on the seabed. Near Italy, in a region of the ocean where *Posidonia oceanica* (see bit.ly/3N5JDQY), a sea grass known as the blue lungs of the Mediterranean, covers the seafloor, it was observed that the time variability of the ambient sound directionality was synchronized with the hours of daylight. Direct measurement of O_2 in the seawater confirmed that the daily cycle of photosynthesis by the seagrass was the cause. As the grass soaked up dissolved CO_2, it expelled O_2 bubbles that lowered the effective sound speed in the vegetation layer near the bottom. The bubbles also scattered and absorbed energy from the ambient sound field, changing the ambient sound directionality. Thus, just by listening, the health and activity of a plant in the ocean can be determined.

Self-Sensing

Sensing with noise has also been an active area of research in the geophysics and physical acoustic communities. In diffuse sound fields, where sources are spread somewhat evenly in space and not concentrated in one area, it is always possible to retrieve the (empirical) Green's function, which mathematically defines the propagation of sound from one point to another (Lobkis and Weaver, 2001), through the time averaged cross-correlation of ambient sound. In the ocean, the Green's function depends on the seawater properties (temperature, salinity, density) between the source and receiver. The background sound recorded on two hydrophones separated by distances of centimeters to 100s of kilometers can be cross-correlated to find the travel time between them. That travel time can either be used to determine the separation distance between the hydrophones (provided you know the sound speed) (Sabra et al., 2005b) to the sound speed in the medium (provided you know the separation distance) or be used to synchronize the data recording systems' clocks, if you know the separation and the sound speed (Thode et al., 2006). Even when the environment (or Green's function) and the background noise becomes more complex, given a long enough averaging time, the dependence between position, sound speed, and sensor clocks can be resolved (Sabra et al., 2005a).

Passive Acoustic Thermometry

The deep ocean is a vast volume of water capable of absorbing and removing atmospheric heat. Ocean currents carry warm surface waters to the poles, where cooling causes the water to sink and store some fraction of the heat in the deep ocean. However, considerable uncertainty around the functioning and fragility of the ocean circulation system and the extent to which it buffers and softens climate change exists. Thus, measurements of the heat content of the deep ocean are critically important in monitoring and predicting the earth's climate health (Ditlevsen and Ditlevsen, 2023). Still, because of the ocean's vastness, direct ship-based or autonomous profiling float point measurements of temperature in the deep ocean are sparse. Luckily, temperature is the dominant thermodynamic quantity that determines the speed of sound in seawater, allowing acoustics to play an important role in ocean climate monitoring.

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) maintains strategically located hydrophone stations around the globe, designed to have complete acoustic coverage the world's oceans for the purpose of detection underwater nuclear explosions (Bradley, and Nichols 2015). Each station consists of two triangular arrays with a nominal separation (**Figure 3**). The sensors are positioned on the axis of the SOund Fixing And Ranging (SOFAR) channel, the depth at which decreasing seawater temperature and increasing pressure conspire to produce a minimum in the sound speed depth profile. Distantly generated sounds, natural or human-made, can be trapped by refraction about this minimum and travel around the entire world with minimal losses (Munk et al., 1994). The method of computing the Green's function from the time-averaged cross-correlation of ambient sound was used to transform decades of acoustic-monitoring data from these stations into a temperature record of the deep ocean (Woolfe et al., 2015). These measurements provide a spatially averaged estimate of the temperature over the path between the two arrays. In the Atlantic, an acoustic measurement of warming by 0.013° ± 0.001°C/yr was reported, in agreement with the available direct measurements (**Figure 4**).

This measurement of the decadal increase in temperature in the deep ocean provides crucial information on the extent and reach of climate change. The measured increase in the concentration of carbon dioxide in the earth's atmosphere (the Keeling Curve; see bit.ly/47BxriX) provides a stark image of human activity altering the state of the globe's outer layers. **Figure 4** shows the scale and timing of the earth's reaction in the deep ocean, the place most isolated from human activity. The

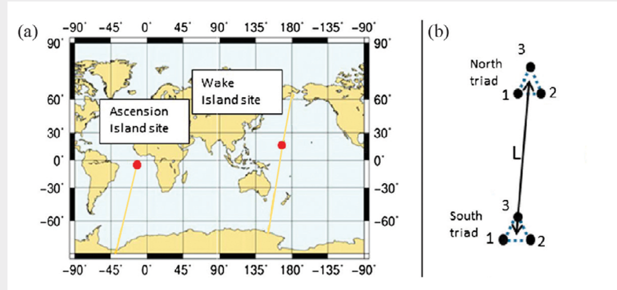

Figure 3. ***a:*** *Location of the two hydroacoustic stations (**red dots**) near Ascension Island and Wake Island.* ***b:*** *Zoomed-in schematic of the hydrophone array configurations for the Ascension Island and Wake Island sites. Each hydroacoustic station consists of a northern and southern triangle array of three hydrophones or triad, with each triangle side having a length of ~2 km. The distance (L) between the triad centers is equal to 126 and 132 km for the Ascension Island and Wake Island hydroacoustic stations, respectively.* ***Yellow lines*** *in a join the centers of the northern and southern triads. Adapted from Woolfe et al. (2015), used with permission.*

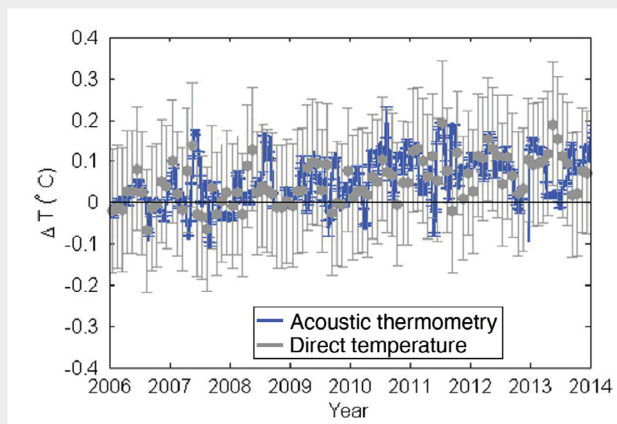

Figure 4. *Comparison of the deep-ocean temperature variation at the Ascension Island site as estimated from passive acoustic thermometry (**blue lines**) with direct temperature measurements (**gray dots**), along with the corresponding error bars. The data series is normalized so that a linear fit on the data would have a y-intercept at zero. The low error bars on the acoustically measured temperature in the deep ocean allows the linear trend of 0.013° ± 0.001°C/yr to be resolved. Adapted from Woolfe et al. (2015), used with permission.*

measurement highlights the ability for passive acoustics to monitor in one of the most remote and hostile places on earth over decades, with minimal maintenance and virtually no environmental impact.

Listening to the Sound Speed Profile

In a deepwater setting, it was demonstrated that computing the cross-correlation of the ambient sound field could be used to determine the ray travel times between all elements of horizontally separated vertical line arrays (Godin et al., 2010). The set of all rays can then be used to estimate the sound speed profile. In shallow water, the sound field can be represented as a set of vertical normal modes, standing waves trapped between the surface and the seabed, propagating in horizontal directions. Each mode has a characteristic speed of horizontal propagation called the group speed. The mode shapes and group speeds are determined by the properties of the seabed and the depth-dependent sound speed in the water column. By estimating the mode speeds and shapes from the cross-correlation of the ambient noise, changes in the sound speed profile can be observed just by listening (Tan and Godin, 2020).

Other features of the sound speed profile can be heard indirectly. Thus, the passing of nonlinear internal waves (waves that occur between seawater layers of differing density with amplitudes of ~35 m and periods of ~10 min) could be observed through sound generated by an increase in current along the seabed, leading to an increase in sediment-generated noise (Katsnelson et al., 2021).

The Timbre of Ocean pH

The absorption of sound in seawater is due to the chemical concentrations of the compounds boric acid and magnesium sulfate in the water. These compounds are in solution, and their exact concentration depends on the temperature and pressure of the seawater. As a sound wave passes through seawater, the chemical reactions of ionic disassociation are driven forward and backward by the increase and decrease of acoustic pressure. This effect, known as chemical relaxation, defines the shape of the frequency-dependent absorption curve. Boric acid releases a hydrogen ion (H^+) when is disassociates, so its concentration is a direct measure of pH.

Using an autonomous acoustic profiler, like the Deep Acoustic Lander (**Figure 5**), a continuous broadband

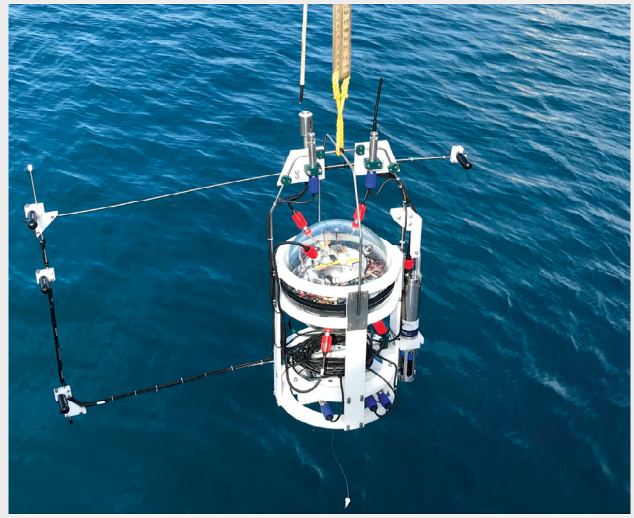

Figure 5. *The Deep Acoustic Lander is a fourth-generation full-ocean depth-rated free-falling acoustic-recording platform designed to capture profiles of ocean sound on a four-channel reconfigurable array. In 2021, the device descended, landed, and returned from the bottom of the deepest known spot in the world's oceans, the Challenger Deep in the Mariana Trench.*

measurement of acoustic absorption can be made using the sea surface as the source as the sensor descends away from the sea surface. When local winds are greater than 10 m/s, the ambient-noise field in the deep ocean is dominated by locally generated surface noise (Barclay, 2013). The breaking-wave-generated sound field has a depth-independent directionality, a weak frequency, and a depth-dependent intensity due to sound absorption. When two measurements of the power spectral density of ambient sound are compared from two different depths with a separation of more than 100 m, the spectral slope of the deeper measurement will be steeper. This is due to the longer propagation path between the source and receiver and the frequency dependence of the absorption. Higher frequencies are attenuated more rapidly than lower ones; thus the spectral slope will steepen with depth. This depth-dependent character of the spectrum of the wind-driven surface wave sound can be used to determine the frequency dependence of the absorption and thus the pH.

Just by listening to the timbre of the background sound, measurements of pH allow the acidity of the ocean to be monitored with hydrophones. Ocean acidification has a negative impact on ocean species like oysters and corals, who make hard shells and skeletons by combining calcium and carbonate from seawater.

This method is analogous to (passive) optical absorption spectroscopy, where the compositions of atmospheres of distant exoplanets are remotely sensed using light from a star of convenience. Unlike optics, which exploits sharp spectral lines associated with different atoms, acoustic absorption spectroscopy only has the slow change in the absorption spectrum of seawater, with frequency driven by the relative concentration of boric acid and magnesium sulfate.

The Future of Passive Acoustic Sensing of the Ocean

Acoustical oceanography is primarily a branch of science and engineering focused on the development of methods. Innovation in measurement, signal processing, remote sensing, and inversion are constant and inevitable within the talented cohort of researchers found in **References**. Adoption of these techniques by the wider oceanographic community will depend on the visibility of the science and the transdisciplinary relationships of physical, biological, and chemical oceanographers and climate scientists. If we continue to ask what we can learn simply by listening to the ocean, recent history shows that passive acoustical oceanography will continue to provide robust, inexpensive, low-power, precise, and accurate measurement techniques to be applied to some of the most important natural science problems on earth.

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Soundscapes in the Postpandemic Era

André Fiebig and Brigitte Schulte-Fortkamp

Introduction

From 2019 to 2022, the world went through the disaster of the COVID-19 pandemic. It was a dramatic period during which people were isolated, when businesses shut down, and when traffic by air, land, and sea declined significantly. Clearly, COVID-19 has been so much more than a health crisis (Adhanom Ghebreyesus, 2023). Due to the pandemic restrictions that affected all areas of personal and professional life, new formats for business meetings and social communication were developed and established to overcome the loss of real-time, in-person interactions with colleagues, friends, and family members. The home office became popular, as did meeting on virtual platforms for conferences or friendly exchanges, eliminating the commute to a workplace and travel to corporate or scientific meetings that required taking planes, trains, or cars. For many people, the home environment has continued to be the place where personal and professional daily activities take place (Torresin et al., 2021).

Lynch and Church (2023) reviewed the COVID-19 pandemic as a global event that not only affected social aspects of human life but also affected the acoustics of soundscapes everywhere. There is overall agreement that the pandemic led to dramatic changes for all living situations. Regarding acoustic environments, there was a reduction in the number of trips by automobiles and commuter trains. The significant drop in traffic led to soundscapes with a reduction of the overall sound pressure level due to the pandemic in general and the lockdown in particular, but there were also perceptual shifts and long-term changes in human activities and their acoustic environments (e.g., Yildirim et al., 2022).

Figure 1 illustrates the result of a co-occurrence network analysis (van Eck and Waltman, 2014) using title, abstract, and keywords to indicate the focus of soundscape studies in the context of the COVID-19 pandemic (VOSviewer version 1.6.19; see vosviewer.com). Different clusters appear with frequently found items related to noise effects and other environmental aspects (e.g., air quality) as well as health- and traffic-related topics. Remarkably, published analyses of psychological, emotional, and perceptual aspects of pandemic-induced behavior are rare and additional studies are needed.

After three years of impacts from the COVID-19 pandemic, both scientific and media sources claim that we have entered a new period: the postpandemic era. This conjecture was recently supported by the World Health Organization (WHO; 2023), which has stated that although the COVID-19 disease is entering its fourth year, surveillance has declined dramatically, and countries should transition from critical emergency response activities to long-term, sustained COVID-19 disease prevention, control, and management. Accordingly, Tedros Adhanom Ghebreyesus, Director-General of the WHO, declared in May 2023 that COVID-19 is over as a global health emergency (Adhanom Ghebreyesus, 2023). Similarly, the United States Department of Health and Human Services (2023) declared the end of the COVID-19 public health emergency on May 11, 2023. In addition, German health experts are talking more and more about a transition from the pandemic response to addressing an endemic disease (Rabe-Menssen et al., 2023). These developments and the increased use of the term *postpandemic* in a wide variety of contexts suggest that social and professional aspects of life in general and, of particular interest for this discussion, soundscapes, have changed again.

Postpandemic soundscapes can be described as soundscapes that take place after the pandemic has ended, whether as an outcome of new developments and social change or as an approach to former soundscapes as experienced before

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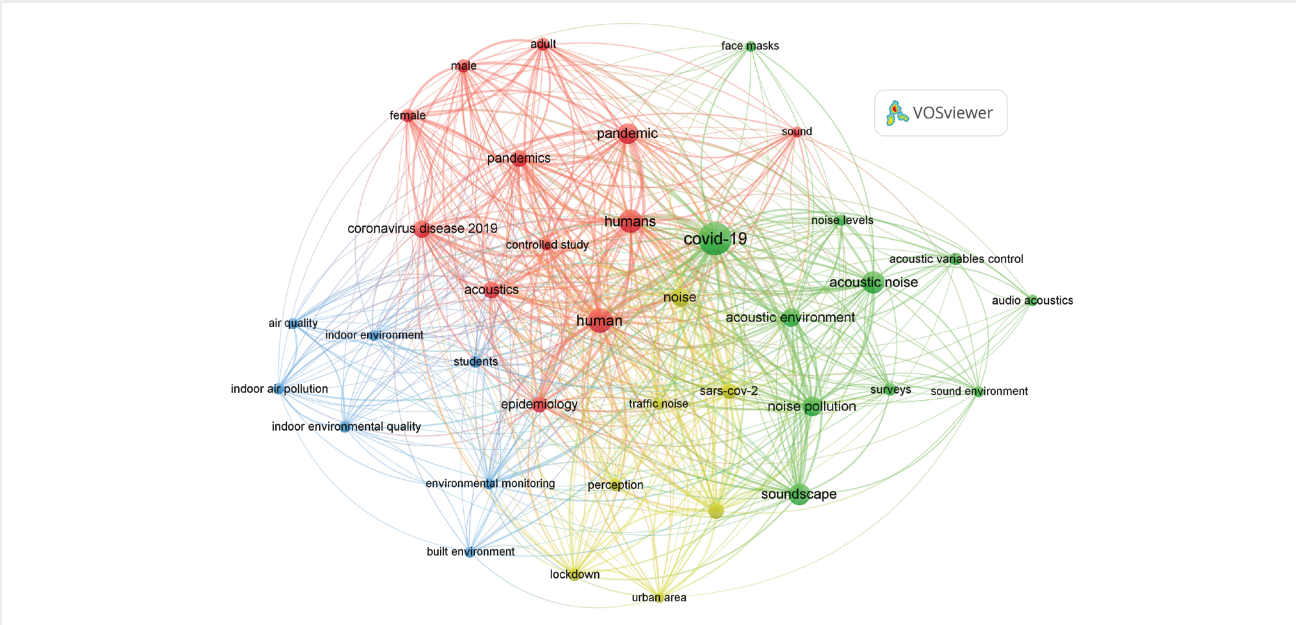


Figure 1. *Map of co-occurrence network of 183 papers found in Scopus searching for "soundscape, acoustic environment, COVID-19, pandemic." Titles, abstracts, and keywords were considered for the co-occurrence network analysis. Terms closer to each other and the same color are terms that co-occur more frequently. Items with fewer than eight occurrences were removed. Created using VOSviewer (see vosviewer.com).*

the pandemic. In May 2023, a conference organized by the WZB Berlin Social Science Center featured discussions of responses to the COVID-19 pandemic, in particular asking whether human activities would simply return to normal in these times of climate change and geopolitical crisis (WZB, 2023). Questions on how to combine work and social life in the future; on how technological, political, and social changes affect daily life; and on which long-term changes might affect how future populations live together were addressed at the conference. The answers are still unclear.

Researchers assert that the COVID-19 pandemic offered a unique opportunity to test soundscapes and assess how the outdoor and indoor living environments changed under extreme circumstances (Bartalucci et al., 2023). Similarly, Hasegawa and Lau (2022; also see Hasegawa and Lau, 2024) concluded that the COVID-19 pandemic will substantially influence numerous facets of daily lives for years. A number of studies explored pandemic impacts on soundscapes worldwide, and there are multiple studies that quantified changes in sound pressure levels in cities due to less traffic (e.g., Haselhoff et al., 2022), but there is little research thus far that provides a better understanding of the effects of those soundscape changes on humans. In addition, the previous efforts have not been reviewed comprehensively or systematically, which reflects a lack of prospective soundscape goals based on the available global evidence (Hasegawa and Lau, 2022).

This article presents observations and findings made over the last year about the pandemic consequences on soundscapes and poses questions to be addressed for better soundscapes in the future, taking into account appropriate social and technological changes. The following questions are considered.

(1) Are there consistent changes in soundscapes that can be described as postpandemic soundscapes?
(2) Do postpandemic soundscapes represent novel soundscapes or a return to previously described soundscapes from times before the pandemic?

Soundscapes During the COVID-19 Pandemic

The pandemic response, especially the drastic lockdowns imposed by governmental authorities in which people were required to limit activities and public contact outside of the home, resulted in extended confinements and behavioral changes in all areas of life. For example, people tended to get

Figure 2. *Impacts of the pandemic: empty restaurants, deserted playgrounds, and lack of tourists, for example, at the Berlin Wall Memorial in Berlin, Germany. Photos by A. Fiebig and B. Schulte-Fortkamp.*

less exercise (Manz and Krug, 2022), generally had a lower activity rate, and traveled less. In addition, people tended to buy more products and food online, socialized less regularly in clubs or restaurants, and spent considerably more money on digital media content and streaming services. Most students indicated more difficulties in coping with examinations. The former sense of "normality" was affected as established routines were suspended (see **Figure 2**).

Those forced and drastic changes in behavior also had an impact on health. Studies have established that the COVID-19 pandemic created an environment in which many determinants associated with poor mental health were exacerbated (COVID-19 Mental Disorders Collaborators, 2021). Meta-studies after the SARS-CoV-2 infection provided indications that mental illnesses were diagnosed more frequently (Rabe-Menssen et al., 2023). One international meta-study showed an increase in symptoms of depression among children and adolescents during the COVID-19 pandemic in a prepandemic comparison; the evidence indicated that the pandemic-related restrictions were a major cause (Ludwig-Walz et al., 2022). The reasons for pandemic-associated mental disorders in children and adolescents are manifold and range from loss of daytime structure and reduction of social contacts to increased conflicts in the parental home (Plötner et al., 2022).

Restrictions that limited contact among people also caused significant adjustments in work and business. During the pandemic, the number of persons who had a "home office" increased significantly compared with before pandemic times, and this included both part-time home office workers and full-time home office workers (Hans-Böckler-Stiftung, 2021). These types of substantial changes that are related to everyday procedures and routines affect urban and rural acoustic environments alike.

From 2020 to 2023, several studies explored the impacts of the COVID-19 pandemic on the environment, focusing on vehicular traffic flows, sound pressure levels, and air quality, to deepen the understanding of the repercussions of the pandemic on environmental pollution and the well-being of individuals (Hasegawa and Lau, 2022). Lecocq et al. (2020) showed that high-frequency seismic oscillations, which are highly correlated with anthropogenic mobility behaviors, decreased worldwide by 50%. According to the authors, the pandemic changes in mobility caused the longest and the most prominent quiet period of high-frequency seismic oscillations on record.

Additional topics were covered in *The Journal of the Acoustical Society of America* (2023) Special Issue on the COVID-19 Pandemic Acoustic Effects. Various acoustic phenomena were linked to the effects of face masks on speech production, speech intelligibility, and acoustic changes in speech, which also affected recall performance due to speech intelligibility and degradation. Changes in noise levels in buildings and in urban soundscapes were also documented. With respect to acoustic environments, some studies focused on the reduction of overall environmental noise (e.g., Alsina-Pagès et al., 2021), whereas others evaluated level changes related to specific sound sources such as air traffic noise (e.g., Greco et al., 2022).

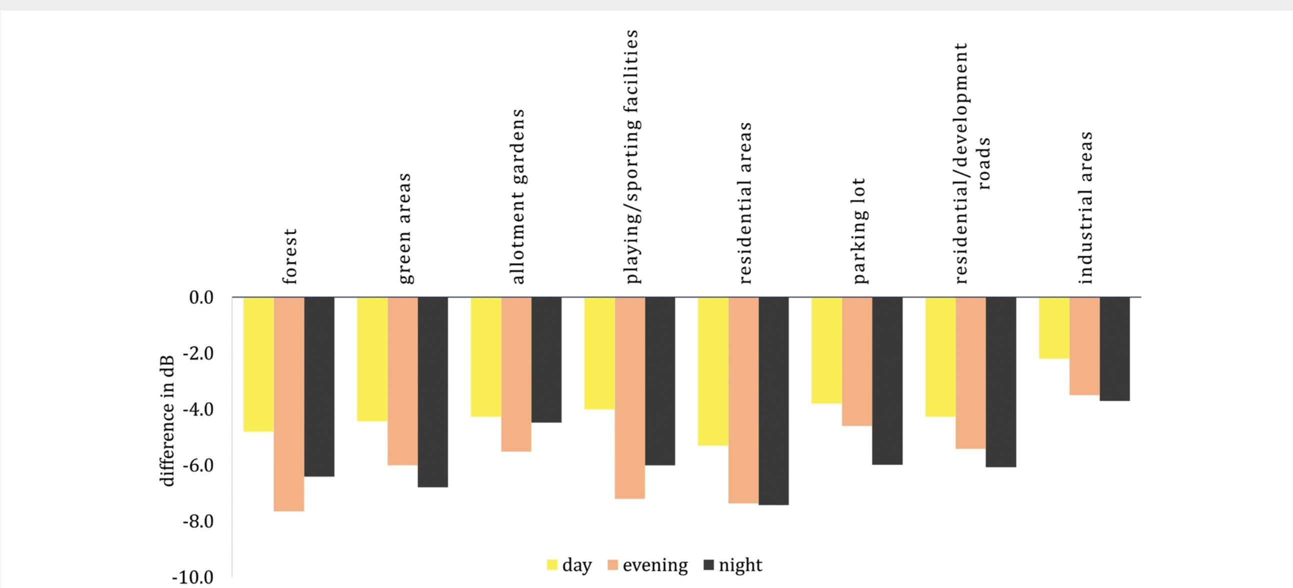
In the context of acoustic environments, most of the research has focused on the impact of governmental restrictions (intended to prevent and control the spread of the virus) on the acoustic environments as measured in terms of sound pressure levels. Researchers observed COVID-19 impacts on urban noise on the country level, city level, or even individual level of experience (Hasegawa and Lau, 2022). Monitoring campaigns were designed, and projects were set up to collect recordings and metadata sets of sounds during the period of the COVID-19 pandemic (cf. Bartalucci et al., 2020). Those studies reported repeatedly on significant reductions in traffic noise in urban areas that led to level reductions of several decibels (Hornberg et al., 2022.; Aumond et al. (2022) determined that the lockdown had a drastic impact not only on the overall sound levels but also on the activity of sound sources in the urban environment. Alsina-Pagès et al. (2021) observed that anomalous noise events increased during lockdown in Milan and in Rome but returned to the former condition in the postlockdown period. As expected, the degree of level reductions varied over land use types (see **Figure 3**). Alsina-Pagès et al. (2021) observed in Girona, Italy, that there were drastic changes in the A-weighted energy-equivalent continuous sound pressure level (L_{Aeq}), especially in areas of the city that previously had an active nightlife, moderate L_{Aeq} changes in commercial and restaurants areas, and only low L_{Aeq} changes in dense traffic areas. Altogether, analyses of the sound levels in numerous studies showed an average decrease in energy-equivalent sound pressure levels of about 5-10 dB(A) (cf. Aumond et al., 2022).

Unfortunately, although many studies in multiple cities focused on decreases in urban noise levels due to stay-at-home orders during the COVID-19 pandemic, fewer studies have examined noise complaints using municipal noise complaint data collected during the pandemic (cf. Ramphal et al., 2022). However, it seems that online tools and surveys were increasingly popular because people were at home, and they could easily participate in online surveys.

Regarding noise complaints, the pandemic seems to have created an inconsistent picture. Unexpectedly, the number of noise complaints increased and decreased at the same time, for example, with respect to specific noise sources considered, e.g., transportation noise versus construction noise (Yildirim et al., 2023). This shows that when considering pandemic-related noise complaint behaviors, there is no one-size-fits-all pattern. However, when examined from a global perspective, it seems that complaints related to traffic noise decreased during the pandemic, whereas the perceptual relevance of construction and neighborhood noise seemed to increase (Tong et al., 2021).

According to Maggi et al. (2021), confinement brought a decrease in mechanical sounds during the lockdown and an increase in audible biological sounds that were associated with feelings of tranquility and happiness. However, behavioral changes and confinement measures also significantly affected the number of noise complaints. For example, in Zurich, Switzerland, the reduction in aircraft traffic led to a significant decrease in aircraft noise complaints (Neue Züricher Zeitung, 2021); however, at the same time, new noise conflicts apparently occurred. Because people were forced to spend a lot of time at specific safe

Figure 3. *Sound level reductions at different times of day at various locations due to the pandemic-related lockdown in April 2020 compared with 2019 in the city of Bochum, Germany. Adapted from Fiebig et al., 2021.*



locations outside (e.g., parks), an increase in the number of recreational noise complaints was observed in many places.

In the Park am Gleisdreieck in Berlin, the number of noise complaints due to leisure noise increased by 10 from 2019 to 2021 (*Berliner Abendblatt*, 2022). Consequently, a member of the Berlin State Parliament concluded that the need and demand for outdoor lounging has grown significantly because of the pandemic, especially in districts of the city that are undersupplied with green spaces. On the other hand, at the Berlin Wall Memorial, level differences of only a few decibels were observed compared with nonpandemic conditions due to the character of the memorial site (Jordan and Fiebig, 2021).

Several studies considered changes in noise levels received or generated indoors. In Zurich, almost 50% more complaints about party noise were observed during the pandemic in 2021 compared with before pandemic times (Neue Züricher Zeitung, 2021). In India, an online cross-sectional survey showed that people assessed indoor environments as noisier during the 2020 lockdown, which adversely affected productivity and online education and was attributed to increased home entertainment usage, video calling, and family interactions (Mimani and Nama, 2022).

In the United States, noise complaints in New York, New York, increased the most in the most economically distressed communities, contrary to some evidence of urban quieting in other places (Ramphal et al., 2022). Economic distress was increased for many individuals because businesses and restaurants closed during the COVID-19 pandemic and unemployment caused more people to be at home.

Based on their review of hundreds of studies related to the impacts of COVID-19 on soundscapes, Hasegawa and Lau (2022) concluded that although beneficial aspects of the COVID-19 pandemic on soundscapes were identified, substantial adverse consequences were observed for human health and well-being. Locations previously dominated by traffic noise were judged as more pleasant. On the other hand, locations that previously had been human- and natural-sound dominated tended to become less pleasant despite the sound level decrease (Mitchell et al., 2021).

All in all, the impacts of the COVID-19 pandemic on soundscapes were varied and site dependent, creating a heterogeneous, complex picture. Reduced traffic noise as well as changed social interactions and routines affected soundscapes in ways that were beneficial and disadvantageous at the same time.

Are We Back to the "Old Normal"?

If we consider the period before the COVID-19 pandemic as the old normal and the current period as a kind of post-pandemic era based on official declarations of the end of the public health emergency (Adhanom Ghebreyesus, 2023; Department of Health and Human Services, 2023), we can investigate and compare the characteristics of the old and new soundscapes. Although some of the current levels of environmental noise appear to approximate the noise burdens from the times before COVID-19, that does not automatically result in a similar perception and assessment of the acoustic environments by humans. Permanent noise monitoring systems frequently document sound levels that indicate a return to "normal" sound levels as measured prior to the pandemic in many places. At the same time, Carfagni et al. (2023) determined that in areas less affected by road traffic noise, the current noise levels seem to be lower than in 2019, maybe due to a change in the habits of local citizens. Moreover, Bartalucci et al. (2023) conducted extensive interview-style surveys and claimed that a comparison of pre/during COVID restrictions and post-COVID perceptions highlighted a different perception of soundscapes in the postpandemic period compared with the period before COVID-19 spread. New functions of home life, such as consistently working from home in spaces designated as a home office, will continue in the postpandemic era. Over recent years, the proportion of people working in a home office has increased steadily (HBS, 2021). Detached home dwellers and apartment building occupants have a new vulnerability to the acoustic conditions around their home when there is a home office, resulting in more demand for high-quality acoustic environments (Torresin et al., 2021).

The present cannot be reliably understood and assessed without considering the repercussions from the past. Therefore, proper assessments of postpandemic soundscapes require a consideration of the immediate aftereffects of the pandemic. What happened to people during the pandemic period of restrictive confinements? How do those experiences color the understanding of everyday life and, perhaps, set new requirements due to changing expectations and behavior?

Scientific findings of pandemic-related mental health effects are sufficiently available to allow valid assessments. Moreover, the pandemic appears to continue to have had a strong impact on mental health. For example, the proportion of children with mental health problems rose during the pandemic until the beginning of 2021 and then fell slightly by the end of 2021 and has stagnated since (Kaman et al., 2023).

A similar trend was found for self-reported symptoms of anxiousness and depression (Kaman et al., 2023). These pandemic-related aftereffects need to be studied to assess their meaning and to facilitate evaluations of health-promoting environments. The role of social changes and health effects cannot be assessed through acoustic analysis alone (e.g., simple noise level measurements); collaboration across multiple disciplines is required, which is the basis of the soundscape concept with its holistic perspective. For economically distressed communities, noise conflicts were even exacerbated during the COVID-19 pandemic, and thus appropriate community-based interventions are needed (Ramphal et al., 2022).

As Lercher and Dzhambov (2023) pointed out, soundscape approaches have provided useful input for small-scale environmental assessments, and soundscape considerations must be more closely integrated with ongoing or future large epidemiological studies. The most relevant evidence-based factors must be considered, but multiple pathways or options should be determined via moderation and mediation analyses while bearing in mind important confounders revealed in other studies (Schulte-Fortkamp et al., 2023). This approach is essential if we are to determine and understand pandemic-related health burdens.

Changes and Challenges for the Future

Current times that are classified as "postpandemic" must be examined from a multidisciplinary viewpoint. The question for the meaning of the postpandemic era for soundscapes has many facets, especially regarding new habits, behaviors, and expectations. The role of those changes cannot be simply interpreted in terms of lower or higher loudness because volume alone is not a consistent predictor of human perception (Schulte-Fortkamp et al., 2023).

Schulte-Fortkamp (2023) emphasized that work-life-balance aspects gained in significance during COVID-19 and modified what was perceived as human needs. Among other possibilities, postpandemic soundscapes could reflect changes with regard to pioneering city planning that involves the concepts of smarter growth and smarter cities based on soundscape techniques that can be applied to urban planning. It is more important than ever to bridge soundscape research and community practices with an understanding of how people react to different types of sounds, behaviorally and psychologically, in specific contexts (Aletta and Xiao, 2018). All those endeavors should mirror the established definition of soundscapes: any acoustic environment perceived or experienced and/or understood by a person or people in context (International Organization for Standardization 12913-1:2014, 2014), putting human perceptions in the center of the research. Soundscape research, due to its interdisciplinary background, offers a broad variety of methods and tools to approach the topic of pandemic-related aftereffects appropriately (Fiebig and Schulte-Fortkamp, 2020).

Habits and Expectations

A long list of changes were caused by the COVID-19 pandemic, from less noise and new needs for work-life balance, from depression to enthusiasm, and from daily needs to new viewpoints on what is the best daily life. Everyone is aware of those complex, ambiguous feelings. The dramatic changes in all living situations left their mark at the individual level as well as on cultural and social levels, which has led to questions about previous quality-of-life requirements.

Bartalucci et al. (2023) observed new social habits and soundscape perceptions. They concluded that new soundscape design is needed and public outdoor spaces need to be enhanced. There are new preferences related to the inclusion of natural sounds, which are given a high preference for enhancing soundscapes.

COVID-19 restrictions caused a serious change in human habits that will give preferred soundscapes a different character in the future. Daily life changed worldwide and new habits had to be developed, starting with establishing home offices and home schooling with the family living together 24/7 in small spaces, adapting to massive restrictions for traveling and the reduction in face-to-face encounters during lockdowns. At the beginning, pandemic-related guidelines and restrictions caused irritation and evoked feelings of helplessness for a large proportion of the population; habits were changed, especially in daily routines. How these pandemic-related changes in human habits will impact established soundscapes and how the associated effects will influence the future designs of soundscapes to benefit human social processes remain to be seen.

Conclusions

The COVID-19 pandemic had an impact on all aspects of life worldwide. Pandemic-related restrictions changed everyday activities, altered the working environment for many, affected education, and changed social interactions and social life. Due to these changes, the acoustic environment was affected as well. Many restrictions in general, and lockdowns in particular, led to significant changes of urban acoustic environments around the world. The pandemic-related confinements led to a reduction in sound levels in urban and suburban areas worldwide and a changed perception of soundscapes due to the significant decrease in traffic noise and other human-generated noises (Asensio et al., 2022). Thus, the COVID-19 pandemic response significantly affected environmental noise and modified urban soundscapes, opening an unprecedented opportunity for research in the field (Asensio et al., 2020). Changes in urban noise due to the pandemic were documented in countries around the world, including Argentina (Maggi et al., 2021), Germany (Haselhoff et al., 2022), and India (Kumar et al., 2022).

Acoustic changes resulted in beneficial as well as negative outcomes (Hasegawa and Lau, 2022), which illustrates the complex impacts of the pandemic on soundscapes. In addition, the long-term implications of the pandemic effects remain to be studied. What are prospective soundscape approaches for the current, postpandemic era? Soundscape design can be guided by the United Nations sustainable development goals to support resilient soundscapes after the pandemic and to enhance healthy living and human well-being in view of the social changes (e.g., home office prevalence) that are already known (Hasegawa and Lau, 2022).

Recent studies have shown that the coronavirus pandemic still has a strong impact on mental health, particularly for families and adults younger than 30 years (Erbguth et al., 2023). After the three years of living with the COVID-19 pandemic, psychiatrists and psychotherapists have rated the pandemic's influence on their patients' psychological complaints as very strong (Köhler, 2023). Those observations indicate that a variety of conditions and long-term effects must be investigated further, and mitigating those effects must be reflected in the assessment of the value of various acoustic environments. Collaboration across multiple disciplines is required, which is generally provided through applying the soundscape concept (Schulte-Fortkamp et al., 2023).

Postpandemic era preferences may represent a new direction for soundscape planning and city planning, which may be controlled by new concepts in community living. Moreover, the significance of new soundscape preferences for the long term and the new requirements they imply has also not been researched. Such processes take time.

Up to now there is not enough research on all the facets of life that changed across generations of people during the pandemic response. This calls for interdisciplinary scientific networks to foster international, interdisciplinary joint efforts in soundscape research, like the network Soundscapes of European Cities and Landscapes successfully realized a decade ago (Kang et al., 2013).

Soundscape changes in the postpandemic era can be understood as an opportunity for pioneering city planning involving the concepts of smart growth and smart cities based on soundscape techniques that can be applied to urban planning for communities making the best out of the pandemic response (Brooks, 2023). Taking this opportunity seriously is particularly important in these times of various global challenges, such as climate change and geopolitical crises. The soundscape concept enables informed planning and encourages communication processes through the involvement of relevant institutions, community groups, and individuals to achieve a new understanding of co-creation for livable environments.

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Earwitness to the COVID-19 Pandemic

Yoshimi Hasegawa and Siu-Kit Lau

After the prolonged three-year (2020–2023) fight against the coronavirus disease (COVID-19), the World Health Organization (WHO, 2023a) declared the end of the pandemic as a global health emergency. As a result, most countries have lifted nearly all pandemic-related restrictions and reduced testing and reporting of new COVID-19 cases (WHO, 2023b). People apparently stopped paying attention to the pandemic and merely recalled what happened in the early days of 2020. Many initial restrictions, such as closing schools and workplaces, halting public transportation, and imposing travel bans, were previously inconceivable but had to be implemented for the safety of the public.

From the perspective of the acoustic environment, these initial pandemic restrictions led to the most abrupt change in sound environments that many countries around the world have ever heard. During the initial pandemic outbreak, one remarkable thing that was noticed by many was the silence, which was referred to as *the lockdown acoustics* (Schulte-Fortkamp, 2020). Due to the sudden suspensions of social and commercial activities, cities emptied and were perceived as "dead." Meanwhile, the virus confined people to their homes, limiting the extent of their activities outside and replacing these activities with alternatives inside, which generated more sound at home or exposed people to their previously unnoticed neighbors' sounds. Listening to our everyday surroundings, cities, neighbors, and communities, we were all earwitnesses (one who testifies or can testify to what he or she has heard) to the COVID-19 pandemic (Schafer, 1977).

A large number of studies regarding pandemic acoustics appeared in the literature starting in 2020 and continues to this day. In this article, we explore some of the unprecedented changes in the world's acoustical environments that people observed during the pandemic. In particular, the article is devoted to the human perceptions, experiences, and/or understanding of the sound environments or *soundscapes* (International Organization for Standardization [ISO] 12913-1:2014, 2014) in the context of the COVID-19 pandemic.

Pandemic Soundscape Overview

Starting in the early part of 2020, many scholars explored how different emerging pandemic situations changed various aspects of sound environments. This includes changes in physical noise levels (in decibels) and/or human perceptual changes (e.g., noise annoyance), in the indoor and/or outdoor environments, and in their occurrence from traffic-dominated areas to residential areas. The understanding of these changes and their consequences on inhabitants have been subsequently documented and published (e.g., Hasegawa and Lau, 2022).

The geographical distribution of the research investigations from the scholarly articles and a list of countries by the number of these investigations are shown in **Figure 1**. The majority of investigations (more than 40%) were conducted in Europe (including the United Kingdom), followed by Asia, North America, and South America. Fourteen studies have surveyed multiple countries, and some of them were across different continents (e.g., Europe and Asia). Some multinational or international investigations included countries in West Asia or Africa, yet those regions are underrepresented in the mainstream of acoustic research.

According to their methodologies and procedures, most researchers conducted their investigations, mainly field works including sound measurements and survey administration, during the first year of the pandemic, with the most data collection occurring from March to May. Recall that the WHO declared COVID-19 a worldwide pandemic on March 11, 2020 (Adhanom Ghebreyesus, 2020). Researchers were then urged to quickly respond to the drastic changes in acoustic environments in many countries across the world that resulted from the pandemic.

https://doi.org/10.1121/AT.2024.20.1.28

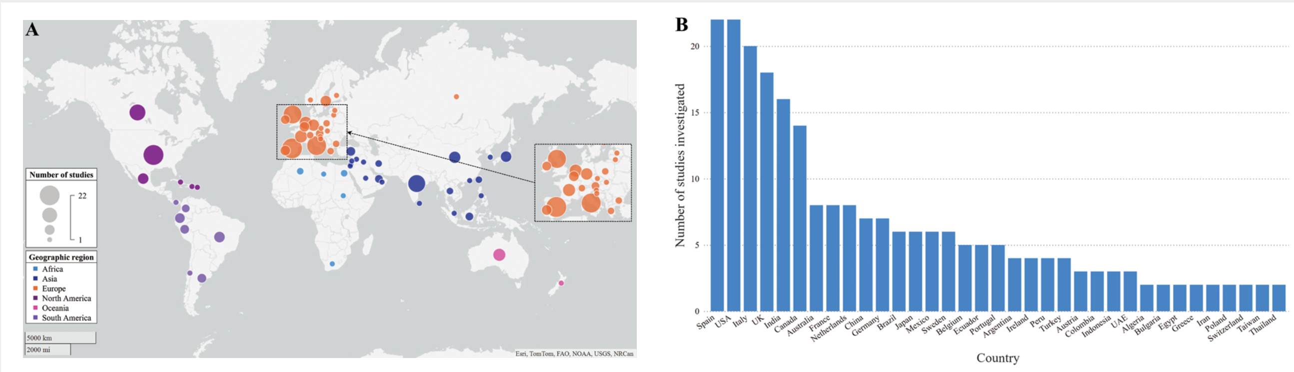


Figure 1. *Geographical distributions of the research investigations regarding sound and COVID-19. Each count is unique and unduplicated by multiple articles sharing the same sample from the same survey.* ***A: circles*** *roughly identify states or provenances where the studies were conducted.* ***Size of the circles*** *represents the number of studies analyzing data from individual countries.* ***Color of marks*** *represents geographical groups. Map generated using MATLAB; Map data sourced from Esri, TomTom, NOAA, FAO, USGS, NRCan.* ***B: number of investigations*** *for countries having at least two investigations. The systematic database search was initially conducted in 2022 (Hasegawa and Lau, 2022) and updated in 2023 (Hasegawa, 2023), resulting in a collection of 175 relevant articles.*

Many researchers collected or externally acquired pre-COVID datasets that had been collected prior to the WHO's pandemic declaration or in previous years (e.g., 2018, 2019). The datasets included those from previous research activities and surveys, other on-going projects that were not initially intended for pandemic-related research, or publicly available databases (e.g., census datasets). Thus, none of those pre-COVID datasets were collected with the thought of using them as pre-/postpandemic comparisons. Yet these comparisons were purposeful and worthwhile in terms of understanding the impacts of the COVID-19 pandemic on soundscapes. There are also 20 unique studies investigating further impacts of the pandemic on soundscapes in 2021 and 2022 (18 and 2 studies, respectively), focusing on subsequent lockdown phases (e.g., the second wave of the pandemic) as well as postpandemic scenarios.

World of the Wrong Silence

Even if people were not aware of their acoustic surroundings before the pandemic, once the pandemic started, many people noticed that many of the sounds normally in their environments were diminished, especially as related to people walking and conversing outdoors or to social or business activities across a neighborhood. The lack of acoustic activities in these soundscapes often induced certain eerie atmospheres in the outdoor environments: the soundscape of the *wrong silence* (Schulte-Fortkamp, 2020; also see a video at bit.ly/48ojCoW for some news about the COVID quietness around the world).

Changes in Outdoor Soundscapes (Noise Level Reduction in Cities)

To scientifically quantify the changes in the soundscape, many acoustic researchers around the world conducted a series of sound measurements in their existing environments. The most common acoustic parameter used in the environmental noise measurements was the equivalent continuous sound pressure level (L_{eq}). The $L_{eq,T}$ is a measure of the sound energy averaged over a given time interval (T) (ISO 1996-1:2016, 2016). For example, $L_{eq,24hr}$ is the sound level averaged over a 24-hour period. Depending on the time interval to which the rating of the sound is referred (i.e., reference time interval), the L_{eq} is recalculated as day (L_{day}), evening ($L_{evening}$), and night (L_{night}) sound levels. The default values (refer to ISO 1996-1:2016, 2016) for each time interval are given in **Table 1**. However, some countries define different reference time intervals, such as L_{day} over the 16 hours from 6 a.m. to 10 p.m. and L_{night} over the 8 hours from 10 p.m. to 6 a.m. (next day) (Government of India, 2000). Furthermore, day-night- (L_{dn}) and day-evening-night- (L_{den}) weighted sound levels are equal to the $L_{eq,24hr}$, obtained after the addition of 10 dB to L_{night} and the addition of both 5 dB to $L_{evening}$ and 10 dB to L_{night}, respectively.

Table 1. *Symbols for day, evening, and night sound levels and default values of their reference time intervals*

Quantity	Symbol	Reference Time Interval
Day sound level	L_{day} (L_d)	Daytime hours: • the 12 hours between 7 a.m. and 7 p.m., or • the 15 hours between 7 a.m. and 10 p.m.
Evening sound level	$L_{evening}$ (L_e)	Evening time hours: • the 4 hours between 7 p.m. and 11 p.m.
Night sound level	L_{night} (L_n)	Nighttime hours: • the 8 hours between 11 p.m. and 7 a.m., or • the 9 hours between 10 p.m. and 7 a.m.

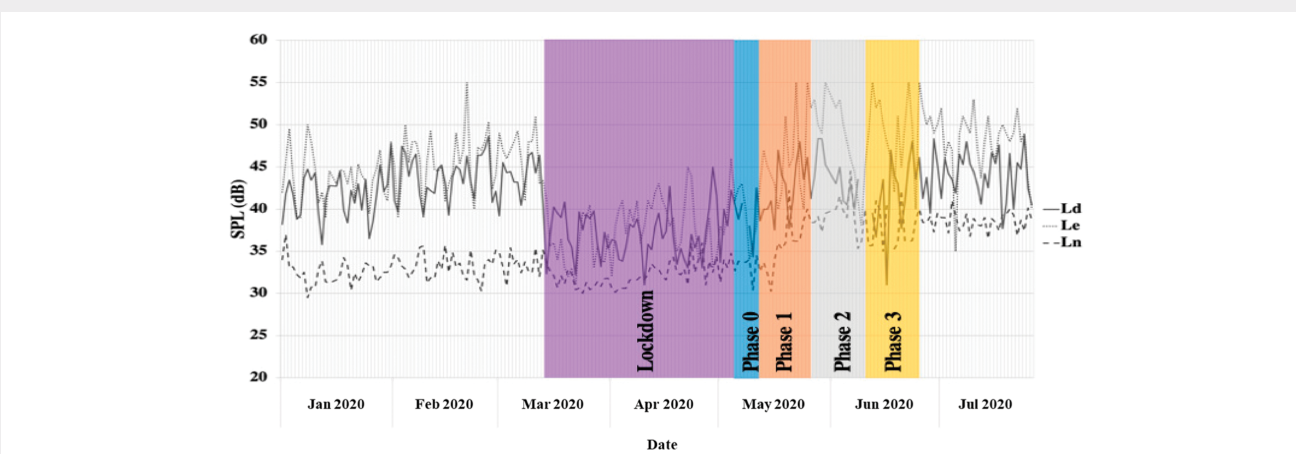
From International Organization for Standardization (ISO) 1996-1:2016, 2016.

In terms of data acquisition, noise-monitoring sensors (e.g., monitoring stations or terminals installed for continuous noise measurements) became one of the most accessible tools for observing changes in environmental noise in cities during the quarantine periods.

Quantitative changes in sound pressure levels during strict pandemic phases clearly differed from their typical prepandemic and postpandemic restriction levels in that the levels dropped in amplitude during restrictive periods (e.g., lockdowns) and reversed after easing the COVID-19 restrictions. This phenomenon is shown in **Figure 2**, which is a time series of the L_{day}, $L_{evening}$, and L_{night} (with the default reference time intervals as provided by **Table 1**) recorded in a high-traffic part of the city of Córdoba, Spain during the pandemic (Redel-Macías et al., 2021). The noise reduction started around the middle of March when the strictest measures were implemented (**Figure 2**, Lockdown). This reduction was especially apparent in the evening and possibly during the day. After the lockdown phase, the noise levels increased, reaching values similar to or higher than before the lockdown by mid-May 2020.

Another example that highlights similar phenomena is the local anthropogenic (human-produced) noise levels measured during the pandemic in New Delhi, India (Mimani and Singh, 2021) (see **Figure 3**). The L_{day} dropped suddenly when the strict lockdown phase 1 was declared. The greatest reduction of 15 dB(A) was observed with respect to the average levels during the prepandemic period as well as the same period in 2019. Subsequently, the levels started to

Figure 2. *Long-term sound pressure level (SPL) recorded throughout all de-escalation phases (i.e., Phases 0-3) and during the lockdown in Córdoba, Spain. The record was provided by the Interlight S. L. Company.* ***Lockdown:*** *citizens were required to stay at home and walks and outdoor sports were not allowed;* ***Phase 0:*** *family walks and individuals' outdoor sports were allowed with limitations.* ***Phase 1:*** *small business activities were resumed.* ***Phase 2:*** *some indoor venues (e.g., cinemas, museums) were reopened with a reduced capacity.* ***Phase 3:*** *capability of stores was increased up to 50%, and mobility between provinces was unrestricted.* L_d*, sound level during the day;* L_e*, sound level in the evening;* L_n*, sound level at night. Adapted (cropped from original and relabeled dates) from Redel-Macías et al. (2021), with permission, used under CC BY 4.0.*



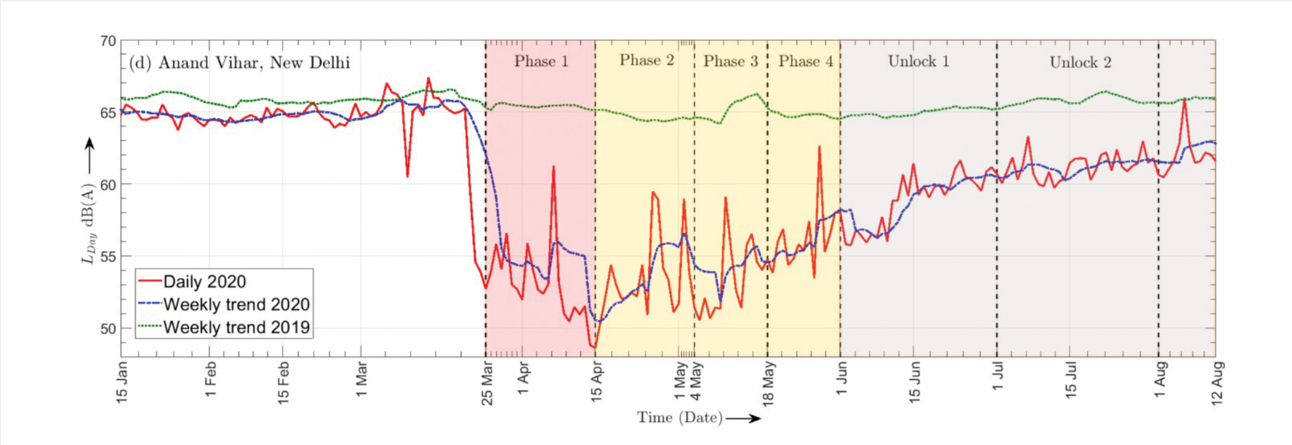


Figure 3. *Daily sound level (L_{Day}) graph for the year 2020 (**red line**) and the weekly trend graph for the years 2020 (**blue line**) and 2019 (**green line**) in Anand Vihar, New Delhi, India. The 24/7 (i.e., 24 hours a day, 7 days a week) ambient-noise levels were recorded by one of the noise-monitoring stations from the National Ambient Noise Monitoring Network (NANMN). **Phase 1:** a complete lockdown was implemented and all transportation services were suspended (the most stringent part). **Phase 2:** almost all the restrictions remained, with some conditional relaxations. **Phase 3:** movement restrictions based on the pandemic situation of different zones were begun. **Phase 4:** it was the least stringent part. **Unlock:** gradual reopening for usual activities. Reproduced from Mimani and Singh (2021), with permission.*

increase from phase 2 onward, slowly reaching close to the prelockdown noise levels. Changes in sounds between prelockdown and during the lockdown in Kolkata, India, are at bit.ly/3t6woZ6 (start at 34 seconds into audio) for reference.

Noise Reductions and Severity Levels

The changes in the temporal variations of noise levels were associated with the adaptation of inhabitants' activity and behavior to the pandemic circumstances (Asensio et al., 2020). Pandemic situations depended on many factors, including the governments' regulations (policies, restrictions, requirements); health care and social systems and capabilities; cultural/social expectations, behaviors, preferences, and attitudes toward the pandemic-related changes; urbanization (urban, suburban, rural) and its morphology of places; and so on. Because our soundscapes are context specific (ISO 12913-1:2014, 2014), it is important to carefully consider the impacts of those pandemic contexts on the world's sound environments.

A significant association between quarantine measures and environmental noise reduction was documented in the early phase of the pandemic (Zambrano-Monserrate et al., 2020). Namely, the more severe the implemented pandemic restriction measures, the greater the resulting noise reduction. To derive global estimates of this association, a meta-analysis was conducted to examine how the noise level reductions varied as a function of the severity levels of such COVID-19 restrictions across many cities worldwide (Hasegawa and Lau, 2022).

Of the acoustic parameters, including 24-hour levels ($L_{eq,24hr}$, L_{den}, L_{dn}) and those in **Table 1**, samples of averaged noise level changes before and after the pandemic restrictions were collected from previously published scholarly articles. A challenge was estimating the strictness of multiple pandemic's precautions and prevention measures imposed by governments from different countries. For consistent estimations, a *stringency index* was collected from the Oxford COVID-19 Government Response Tracker (OxCGRT) (Hale et al., 2021). A stringency index is a composite measure made up of a particular combination of nine policy indicators/response metrics (C1-C8 and H1; see **Figure 4**) and represents the strictness of the "lockdown-style" policies that primarily restrict people's behavior (Hale et al., 2021). It was found that the average noise-level reduction observed during the pandemic varied as a function of the stringency level of the COVID-19 confinement policies imposed by the governments (Hasegawa and Lau, 2022). Clearly, a set of these restrictions had consequences for our total acoustic environment, bringing out an unprecedented silencing on a large scale (Asensio et al., 2022).

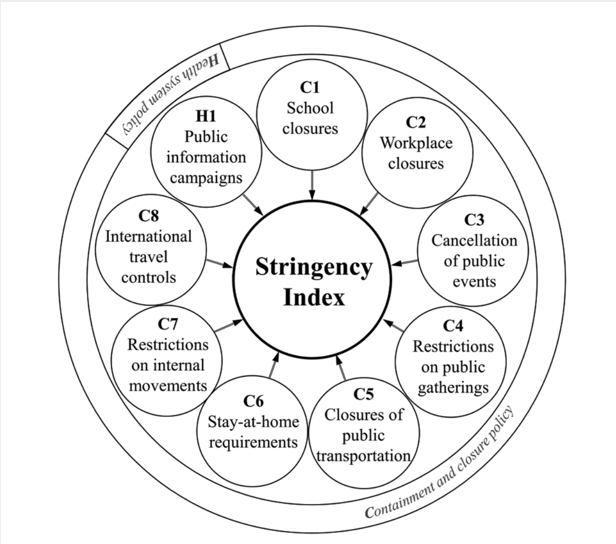


Figure 4. *Each of the nine indicators (C1-C8 and H1;* ***circles with arrows pointing to center****) accounts pandemic-related measures based on two difference policies (containment and closure policy and health system policy;* ***outer ring****), making up a single composite index (Stringency Index;* ***center circle****).*

Enhanced Natural Soundscapes

Soundscapes are created from the integration of various sound sources, including biophonic (animal-produced), geophonic (geophysically created), and anthropogenic sounds, and the number of their interactions (Pijanowski et al., 2011). Given that anthropogenic noises were significantly reduced during the severe lockdown periods, natural sounds (i.e., biophonic and geophonic sounds) were altered as well.

Several studies pointed out that people perceived more natural sounds during the pandemic, frequently referred to as bird chirping, but also the calls of other animals (Di Croce et al., 2022) and the sounds of leaves and the wind (Bild et al., 2022). A French study by Munoz et al. (2020) found that residents clearly perceived a reduction in transport-related noise sources while noting an increase in natural sounds outside their homes. Similar improvements were also observed in urban areas among other European countries (Garrido-Cumbrera et al., 2021). It is possible that a large decrease in anthropogenic noise (or noise pollution) unmasked the existing natural sounds. Moreover, this large reduction potentially alleviated the acoustic pressure on animals that use sound for communication and survival, hence altering their sound-producing behavior. For example, birds increased their singing performance (Derryberry et al., 2020).

The enhanced natural soundscapes resulted in a high restorative quality, potentially reducing pandemic-induced stress and fatigue (Qiu and Zhang, 2021) and, in turn, with better perceived health (Dzhambov et al., 2021) and improved acoustic comfort while working at home (Torresin et al., 2022). Perhaps, the unique array of natural-human soundscape dynamics enabled people to increase their awareness of the sounds from nature.

Cultural and Social Rhythms amid the Crisis

There are other signature sonic signals that emerged during the initial surges of the COVID-19 pandemic. Indeed, people purposely created sounds with particular social, cultural, and ritual emphasis and movements within their contexts. For example, one of the globally expanded movements was the act of *making noise* and *clapping* as expressions of appreciation for the frontline workers fighting against COVID-19. The actions involved people making various kinds of sounds and/or noises from their open windows, balconies, or rooftops. These included clapping hands, clanging utensils (e.g., pots or pans), singing songs, and playing instruments or music. Such practices were known as the 7 p.m. applause in Canada (Catungal, 2021) and were conducted at various other times elsewhere.

Rigal and Joseph-Goteiner (2021) tracked the creation and circulation of these practices that focused attention on the efforts of health care workers. They counted noise-making and clapping practices in 101 countries and 26 global cities spread over the course of several months (e.g., see bbc.in/3PSgt9S for an example in the United Kingdom). The appreciation movements were not limited to health care workers but were also seen for many frontline/essential workers, those who continued working on-site while putting themselves at greater risk of contracting the virus (e.g., food service workers, garbage collector) (Catungal, 2021) (e.g., see bit.ly/46oHkiW for a video of a Broadway star singing for all the essential workers).

Other sound-related movements that emerged during the pandemic were the practice of bell ringing from church towers (see bit.ly/465lAsW) (Parker and Spennemann, 2020) and the public broadcast of the Muslim call to prayer from mosques (see bit.ly/46rgffj) (Riskedahl, 2020), sounds uniquely delivered from religious communities. Given the pandemic-related noise level reduction, both practices created a strong audible presence in the public community with their sound devices.

Because most of these sound-related practices differed in many ways, including social, cultural, and ritual (religious) contexts, people perceived, experienced, and understood the practices very differently. Although the diversity in listeners' soundscapes should be acknowledged, these momentarily signature soundscapes became a way of sharing people's thoughts and feelings during the pandemic period.

Home Sounded Like Chaos

As people stayed and spent more time at home during the early pandemic period, most of their regular activities were moved from the outdoor to individuals' indoor environments. School and workplace closures resulted in mandatory learning from home (LFH) and working from home (WFH) conditions, respectively. Some on-site social gatherings could be replaced by remote or online venues. In addition to at-home daily activities (e.g., relaxing, sleeping), our living rooms or bedrooms were transformed to temporary office spaces or classrooms, becoming multifaceted spaces where all the activities took place to complement our pandemic-induced limitations.

Increased home activities also resulted in increased exposure to noises from adjacent units or neighborhoods. Being within noisy and crowded environments and having no control over the sounds being transmitted from adjacent areas, people felt that their *homes sounded chaotic*.

Changes in Indoor Soundscapes (Affected Human Responses at Home)

The process of researching indoor acoustic environments and corresponding human perceptions or indoor soundscapes was challenging due to the pandemic situation. Most residents stayed at home during the confinement period and discouraged nonfamily members from visiting. Soundscape researchers had to comply with several preventive measures against the pandemic while seeking alternative approaches to conducting their research activities.

To overcome these limitations, most research activities were moved from in situ to virtual venues and many online surveys were rapidly developed and administered. Online surveys were disseminated via various tools and platforms, including social media platforms (e.g., Facebook, Twitter [rebranded as X]), institutions' websites and mailing lists, and commercial and crowdsourcing entities that recruit research participants. One of the common survey questionnaires for indoor soundscape evaluation asked participants about perceived changes in acoustic environments between the prepandemic and during the pandemic periods. For example, Caniato et al. (2021) conducted an international online survey and asked the participants to rate how their perceptions in their indoor noise level at home had changed during the COVID-19 emergency lockdown in comparison to their prelockdown situation (e.g., "quieter" or "noisier"). Although these methods often suffer from significant sampling and recall biases, there were few available options in the early days of the pandemic declaration for assessing the pandemic impacts on the subjective perceptions of their sound environments and addressing their confinement environments (e.g., home).

Residents' health and well-being were adversely affected by the indoor acoustic environments that were transformed due to the pandemic restrictions. Increased neighborhood and indoor housing noises created poor WFH and LFH conditions, resulting in psychosocial, occupational stress. Andargie et al. (2021) found that airborne noise (e.g., people talking) and impact noise (e.g., footsteps, moving furniture) coming from neighboring suites and shared spaces within suites (e.g., roommates and family members) adversely affected residents' WFH ability. Regarding LFH environments, poorer access to a quiet study space was associated with greater difficulty in academic courses, such as more difficulty keeping up with course readings and completing assignments (Telli et al., 2023). The affected indoor acoustic environments also led to increased adverse psychological responses. For example, Dzhambov et al. (2021) found that greater exposure to mechanical sounds experienced during home confinement was consistently associated with both lower restorative quality of the home environment and worse self-rated health. Those adverse consequences of the pandemic indoor soundscapes on people's health and well-being were substantial.

Unrecognized Vulnerable Populations

The adverse changes were exacerbated among people from distressed or vulnerable communities (Hasegawa, 2023), with the term vulnerable including a number of potential factors/statutes associated with individuals' vulnerabilities. These include people 65 years and older and children (physiological vulnerability); people with financial difficulties, low educational levels, unemployment status, and/or social classes (socioeconomic vulnerability); and people from racial minorities (social vulnerability).

There were also clear disparities in noise complaints between socioeconomically disadvantaged groups and their counterparts during the COVID-19 pandemic. By analyzing over four million noise complaints from the New York, New York (NYC) 311 calls (a hotline for nonemergency city services and community concerns), Ramphal et al. (2022) found that noise complaints have increased the most in the most economically distressed communities (lowest income quartile) since 2010 and this disparity was further magnified during the COVID-19 pandemic. Similarly, a United Kingdom study analyzed a noise complaint dataset in London and found a significant increase during the lockdown and that this change was even higher in areas with higher unemployment rates, more residents with no educational qualifications, and lower house prices (Tong et al., 2021).

Many socioeconomic circumstances are often interrelated, including higher unemployment rates, lower educational levels, and lower household income. Such interrelationships may further affect housing quality (Sinha et al., 2017), where low qualities of houses would have degraded properties, including poor structural characteristics such as insufficient soundproofing and sound insulation. People living in such vulnerable housing conditions could be prone to unprecedented changes due to the pandemic; hence, the pandemic widened the disparities in residential soundscape experiences.

The impacts of the pandemic were even amplified for children from vulnerable groups who already experienced poorer health and well-being (Jones et al., 2020). During the 2020 lockdown in Spain, for example, children from families with low educational levels and financial difficulties were more likely to suffer from excessive noise at home, which could have further affected the children's physical and mental health (González-Rábago et al., 2021). Moreover, in the United Kingdom, children from financially struggling families found home learning challenging because of noise and a lack of space in their homes, which resulted in decreased engagement with home learning (Easterbrook et al., 2022).

Although the impacts of pandemic soundscapes on those populations were adverse, only a few such studies have been conducted on these topics. Therefore, prospective research efforts are vital to challenge the inequitable environmental issues, identify viable solutions, and make the research outcomes reachable to much broader populations.

Conclusion: Toward Postpandemic Soundscapes

The remarkable changes in the world's acoustical environments and the corresponding auditory perceptual experiences due to the initial pandemic restrictions were mostly ephemeral and are unlikely to be found now that the pandemic is over. Most research studies conducted in the early stage of the pandemic (March-May 2020) saw it as a rare moment that enabled researchers to measure the baseline sound levels in various environments. However, with the gradual ease in the pandemic restrictions, the outdoor noise levels returned to or were even greater than prelockdown levels (Redel-Macías et al., 2021). As we moved away from the first infection wave and experienced subsequent multiple infection surges, the impacts of the pandemic on our soundscapes changed. A study by Michaud et al. (2022), conducted in April-May 2021 during the third wave of the COVID-19 pandemic, showed that most people reported that the pandemic did not affect their annoyance with environmental and indoor noise.

However, some pandemic-induced lifestyles and behavior changes might persist after the pandemic ends, such as reduced air travel for business, more frequent online shopping, and sustained hybrid work styles (both office and remote working) (Salon et al., 2021). The long-term increase in telecommuting is remarkable in that some people decided to continue staying at home and communicate remotely. Indeed, our future soundscape agenda may need to adjust to the needs of remote workers, including improving the indoor acoustic environments for supporting good WFH/LFH performance as well as a range of activities (relaxation or leisure activities) (Torresin et al., 2022). Flexible and multifunctional environments would promote the livability and the quality of life of residents; hence, these themes are crucial for our postpandemic soundscapes (Hasegawa and Lau, 2022;

also see Fiebig and Schulte-Fortkamp, 2024, for a further discussion of postpandemic soundscapes). Besides, restorative soundscapes (e.g., natural soundscapes) should be promoted for alleviating psychological distress within populations.

The world is moving toward endemicity where COVID-19 may exist as a disease that is constantly present but limited to a particular region or population; however, challenges remain unaddressed. Thus, we must be forward thinking, learning from previous experiences and lessons, and keeping ourselves updated to improve soundscapes and enhance people's health and well-being proactively.

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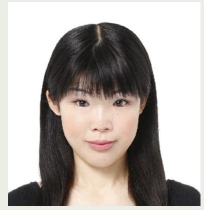

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Mud Acoustics

Charles W. Holland, Stan E. Dosso, and Jason D. Chaytor

Introduction

Long before kindergarten, many of us experimented with mud. Mud's squishiness, the fact that we could launch airborne blobs with a kick or a stomp and the satisfying "thwuuck" sounds that this made provided hours of delightful exploration, sometimes despite protests from our parents. And although most kids outgrow playing in mud, some of us who study sound propagation in the ocean continue to be fascinated by it.

But one might well ask why is mud acoustics interesting and important? The answers are that (1) we live on a muddy planet because oceans cover 70% of the earth and mud covers the vast majority of the seabed; (2) acoustics play a critical role in studying and operating in the oceans because light and radio waves are poorly transmitted in seawater, whereas sound propagates effectively; and (3) acoustic waves in the ocean often interact with and are strongly affected by the seabed. Hence, measuring and understanding the acoustically relevant geophysical properties (referred to as geoacoustic properties) of muds are necessary to apply and predict acoustics in marine environments.

In this article, we provide an overview of mud acoustics by briefly addressing the following questions. What is mud? Which mud properties are important? How are those properties measured, inferred, and modeled? And finally, what is it we still don't know?

What Is Mud?

Marine sediments can generally be divided into two broad categories: (1) granular or coarse-grained sediments (e.g., sand, gravel) in which the individual grains are held together by gravitational forces and (2) fine-grained sediments (muds) in which the grains are held together primarily by electrochemical forces. More specifically, mud is an unconsolidated sediment that must have two components: some amount of microscopic material, be it clay-sized (<4 µm diameter) and/or silt-sized (4-63 µm diameter) grains, and water. Beyond these two requirements, mud may contain almost anything else of any size, such as sand and gravel, organic matter, and microplastics, often making it difficult to determine exactly what is meant when "mud" is used in scientific or engineering applications.

So perhaps it is easier to describe what mud is not because other sediments are well defined. Sediment that is either predominantly (nominally >50% by weight) composed of sand-sized (63 µm to 2 mm) or gravel-sized (>2 mm) material is not mud. Although sand- or gravel-dominated sediments may be described as "muddy" if they have clay- or silt-sized grains incorporated into them, they are not considered to be mud.

Figure 1a shows an optical image of mud. The larger green, brown, and clear grains are minerals worn away from preexisting rocks through weathering and erosion. There is also abundant biogenic (particles produced by living organisms) silt including diatoms (e.g., **Figure 1a**, *large circle*), fragmented plankton shells (fragments with many closely spaced holes), spicules (long needlelike features), clay, and possibly organic matter (disseminated brown material, e.g., **Figure 1a**, above the 50-µm scale bar).

The composition of the materials comprising a mud is vitally important to its geoacoustic properties. Beyond the requirement for water, the composition of mud is primarily a function of the environment in which it occurs. Muds in land-based and marine settings contain a mix of inorganic and organic components derived from local or distant sources. Inorganic components are further divided into minerals from the weathering of nearby rocks; transported phases (e.g., volcanic ash); biogenic materials (e.g., skeletal remains of plankton); and other minerals formed in place by chemical processes. These mineral and biogenic grains have a stunning range of shapes and sizes, from platy clays (layered or sheet crystals) to exotic chambered

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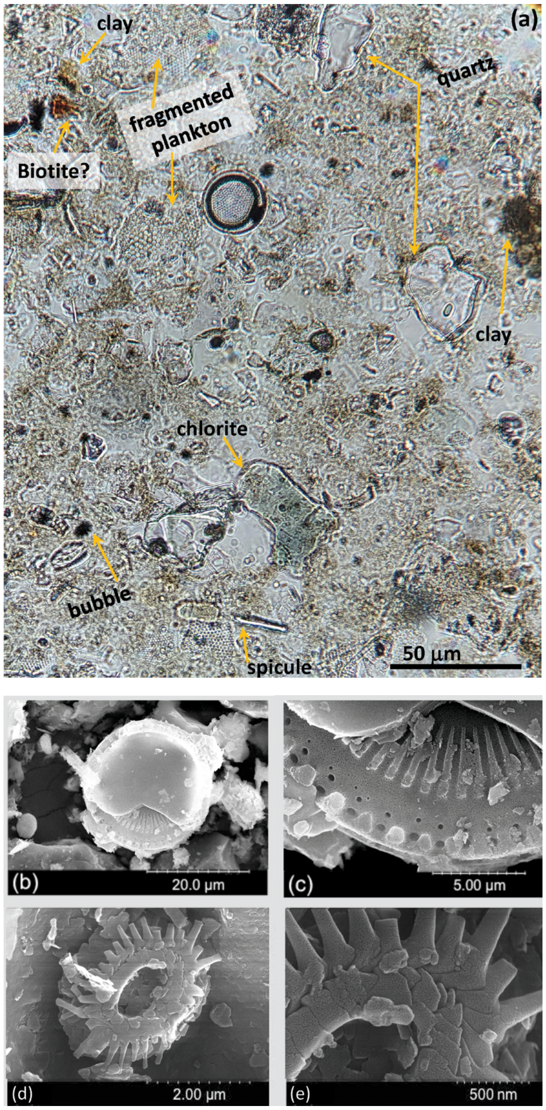


Figure 1. *Images of mud from the New England Mud Patch (NEMP).* ***a:*** *From an optical microscope.* ***b-c:*** *Scanning electron micrograph (SEM) of the remains of a diatom (algae made of silica).* ***d-e:*** *SEM images of a coccolithophore (plankton made of calcium carbonate).* ***Figure 1, b-e,*** *adapted from Dubin et al., 2017, with permission of Acoustical Society of America.*

and ornamented remains of microscopic marine organisms (see **Figure 1, b-e**).

In general, inorganic components tend to dominate the composition of mud. This is the case for a biogenic ooze off the coast of Italy that is almost entirely composed of the fossil remains of single-celled marine algae (85% clay sized). A very different mud composed primarily of land-based grains (15% clay sized) is found in an area known as the New England Mud Patch (NEMP), another site of extensive field studies (Wilson et al., 2020). Both the Italian and NEMP muds are considered further in **Mud Geoacoustics**.

Organic components found in mud come from land-based plant and animal sources and marine organisms (e.g., bacteria, plankton, and larger mobile fauna) that undergo various levels of degradation. The degraded organic matter may suspend silt and clay particles in the sediment fabric or, in other words, restrict the silt and clay particles from touching each other. The organic matter can also adsorb onto mineral surfaces and reside between mineral contacts. All these interactions alter mud properties, decreasing stiffness, increasing viscosity, and decreasing density (Venegas et al., 2022). Biological processes further alter the mud geoacoustic properties through events such as burrowing and tube building of benthic organisms (Dorgan, 2020).

Mud Geoacoustics

The geoacoustic properties of marine sediments that are generally most important in influencing ocean-acoustic propagation are the compressional-wave (sound) speed, attenuation, and bulk density. The shear-wave speed and attenuation in mud can be important in some cases; however, mud shear-wave speeds near the water-sediment interface are typically about two orders of magnitude smaller than the sound speed in mud or water, and, hence, there is little coupling between acoustic and shear waves. Thus, in many cases, modeling mud as a lossy fluid is a reasonable approximation for acoustics.

Sound speed and attenuation in muds and other sediments vary with the frequency of the acoustic waves passing through them. Measuring and understanding these frequency dependencies are challenging but important because they provide clues to the underlying physics that control acoustic-wave propagation in sediments. Geoacoustic properties also depend on the depth below the water-sediment interface. This dependence is important because if the sound speed increases with depth, acoustic waves can be refracted and/or reflected upward back into the water column. Alternatively, if the sound speed decreases with or is independent of the depth, the acoustic energy transmitted into the sediment does not return to the water column.

Measurement and Inference Methods

Geoacoustic properties of muds and other seabed sediments can be determined using two broad approaches:

(1) *Measured directly* using invasive procedures (such as inserting a probe into the sediments or extracting a sediment sample, referred to as a core, for subsequent laboratory measurements), or

(2) *Inferred remotely* using water-column measurements of acoustic fields that interact with the seabed.

In a previous *Acoustics Today* article, Ballard and Lee (2017) termed these approaches *direct* and *indirect*, whereas we use *direct* and *remote*. Although Ballard and Lee focused on direct methods, we discuss remote methods in more detail to fill out the picture. Direct and remote approaches are both important in developing our understanding of mud, and each has its own advantages and limitations.

For direct methods, sound speed and density are routinely measured in cores, whereas attenuation measurements are less common. Probes normally measure sound speed. Although useful information about mud is obtained with direct measurements, limitations on such methods include (1) the unavoidable disturbance and modification of sediment properties from their natural state, especially for muds that are often structurally fragile; (2) restricted sampling depth, with most cores for acoustic purposes penetrating less than 10 m and commonly about 1 m, whereas probes penetrate up to about 3 m; and (3) restricted range of (high) measurement frequencies, with probes operating at kilohertz to hundreds of kilohertz and core measurements at hundreds of kilohertz. Despite these limitations, an important advantage of coring is that the sediment sample is retrieved and can be studied minutely, including the underlying physical properties such as the mineralogy, chemistry, grain-size distribution, and organic-matter content (e.g., Chaytor et al., 2022). These observations can be crucial for developing a fundamental understanding of the relationships between the physical and the geoacoustic properties of sediments.

In contrast to direct methods, remote-sensing methods infer sediment geoacoustic properties from measurements of acoustic fields (data) that have been altered by interactions with the seabed and, hence, carry information on seabed properties. Remote-sensing methods require a theoretical model for these interactions such that acoustic data can be predicted (computed) given a set of geoacoustic properties, with the goal of determining property values for which the predicted data match the measured data (describing methods by which this is done is beyond the scope of this article). This remote-sensing procedure is referred to as geoacoustic inversion.

A variety of at-sea survey methods can be used to obtain different types of acoustic data that can be employed in geoacoustic inversions. Geoacoustic inversions can be based on measurements of either long-range or short-range acoustic propagation. Long-range methods, in which the propagation path is typically 1-10 km long on the continental shelves, involve multiple or continuous acoustic bottom interactions and provide geoacoustic estimates that represent a lateral average of the sediment properties over the propagation path (e.g., Knobles et al., 2020). Such methods are well-suited for estimating sediment properties for regional models and long-range propagation predictions. A limitation, however, is that unknown spatial and temporal fluctuations in the environment (water column and/or seabed) along the path can lead to biases in the inferred properties. Furthermore, detailed sediment-column structure may not be resolved due to this averaging and intrinsic attenuation can be obscured by other cumulative loss mechanisms such as scattering from rough interfaces or volume heterogeneities. Thus, the detailed structure is best obtained using short-range data that interact with the seabed over with a small lateral footprint (10-100 m), such as the single-bounce reflection method considered in this article.

Advantages of remote methods are that they sample undisturbed *in situ* sediments, potentially as deep as a kilometer or more (depending on the acoustic frequency and sediment type), and they can provide information about sound speed, density, attenuation, and, in some cases, shear and other sediment properties. However, remote methods suffer from the fact that acoustic data contain errors (noise) and provide only limited information on the seabed such that the estimated geoacoustic properties always have some degree of uncertainty (dependent on the data type, frequency, and other factors). Also, remote methods are generally limited to the frequency range of tens to thousands of hertz.

One important thing to note is that neither direct nor remote methods provide "ground truth" (definitive knowledge) for geoacoustic properties. Furthermore, as currently applied, the two methods generally cover distinct (nonoverlapping) frequency bands. This means that for the most complete understanding of sediment acoustic properties, both direct and remote methods should be applied. Even then, both modeling (to bridge the frequency gap) and subjective interpretations are required to explain/understand the disparate observations.

Sound Speed

In contrast to coarse-grained sediments, marine muds often exhibit the curious property of having a sound speed less than that of the seawater above. This is a consequence of the weak electrochemical forces that bind the sediment grains together so that muds often behave essentially as a suspension of fine grains within water (unlike sands or other sediments). This suspension has a higher density than seawater but nearly the same bulk modulus (resistance to compression) as seawater because the individual grains form a weak matrix (frame). Thus, because the sound speed depends on the bulk modulus divided by the density, the result is a lower sound speed for mud than for water. This means that the sediment sound speed ratio (SSR), defined as the ratio of the sound speed in the sediment to that of the overlying seawater, is less than one.

The SSR is of considerable importance in ocean acoustics. It can be measured directly by cores or probes or inferred by remote (inversion) methods, with the attendant challenges noted in the previous section. Mud SSR measurements can be challenging. This is evidenced, for example, by widely varying measurement results at the NEMP test site where SSRs ranging from 0.94 to 1.02 have been reported within a small geographic area (Wilson et al., 2020).

A useful remote-sensing method for estimating mud sound speeds (and other properties) involves seabed reflection coefficients. The measurement procedure is illustrated in **Figure 2a**. A hydrophone (underwater microphone) is used to record acoustic pulses from an acoustic source that follow direct and bottom-reflected paths through the water column. The reflection coefficient is defined as the ratio of the reflected wave acoustic pressure to that of the direct wave and thus quantifies how the reflection process has altered the wave amplitude. Measuring reflection coefficients for a range of reflection angles using a towed acoustic source provides an acoustic dataset that contains a great deal of information about seabed geoacoustic properties.

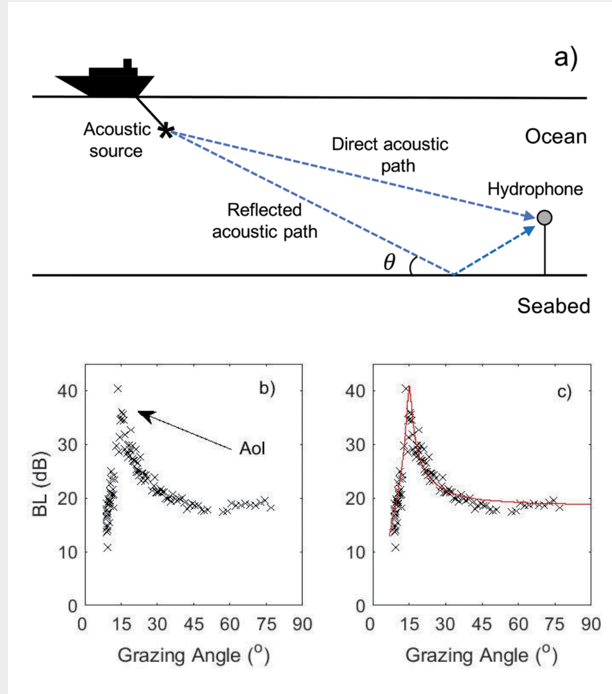


Figure 2. ***a:*** *Reflection coefficient or bottom loss (BL) measurement geometry.* ***b:*** *Measured BL south of Sicily, Italy, as a function of grazing angle θ at 800 Hz, showing a clear angle of intromission (AoI) at 15°.* ***c:*** *Comparison of the measured BL with predicted BL (**red line**) computed using the estimated mud sound speed and density. Adapted from Holland, 2002.*

A particularly interesting case involves data with an angle of intromission (AoI), that is, an angle at which the reflection coefficient goes to zero (i.e., there is no reflected acoustic wave but rather total transmission into the seabed). The AoI was predicted theoretically by Lord Rayleigh in 1896. Rayleigh showed that the AoI exists for reflection at the interface between two media with sound speed and density ratios less than and greater than unity, respectively.

Because muds often have a SSR less than one and always have a density ratio greater than unity, an AoI should commonly occur in seabed acoustic-reflection measurements. However, there have been only a few successful field measurements of the AoI. One reason for this is that it is challenging to measure the absence of something, in this case, the reflected field. Not only does the signal-to-noise ratio have to be high, but all other "contaminating" paths must be mitigated, including reflected waves from deeper layers in the seabed.

The first clear AoI measurement was published by Winokur and Bohn (1968), who found an AoI of 11° in a deep-ocean setting (water depth 4,500 m). The next observation came more than 3 decades later with a measured AoI of 15° in 100 m of water at several sites in Italian coastal waters (Holland, 2002). One of these datasets is shown in **Figure 2b** in terms of bottom loss (BL) in decibels (with high BL corresponding to low reflection coefficients) clearly showing the AoI.

Using measurements of the AoI and BL at one other angle, the seabed sound speed and density can be calculated from Lord Rayleigh's theoretical work, with values of 1480 ± 4 m/s (SSR = 0.979 ± 0.003) and 1.32 ± 0.04 g/cm^3, respectively, at this site. Using those geoacoustic estimates, the full BL can be calculated theoretically, which compares closely with the measured data (see **Figure 2c**). These data, collected south of Sicily, have the same AoI as data at the same water depth 1,000 km away in the Tyrrhenian Sea, north of Elba Island, Italy (Holland, 2002). This suggests that the physical processes that govern the mud microstructure are likely similar at the two sites.

Depth Dependence

The approach above estimated depth-independent mud geoacoustic parameters using the AoI at a single frequency. But what if the AoI is observed to be frequency dependent? It is well-known that the acoustic penetration depth in sediment decreases with frequency (increases with wavelength) such that very high frequencies (short wavelengths) are sensitive only to near-surface geoacoustic properties, whereas low frequencies (long wavelengths) are sensitive to deeper properties. Thus, depth-dependent sound speed and/or density profiles lead to a frequency-dependent AoI.

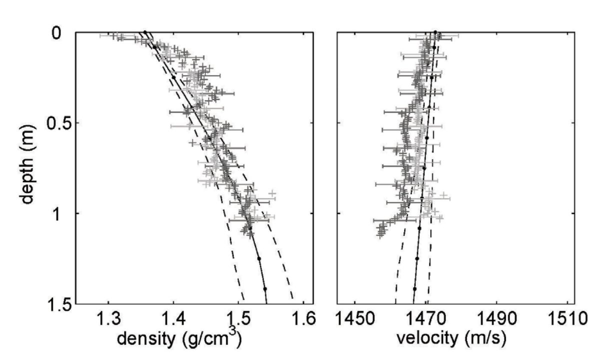
Conversely, frequency-dependent AoI observations provide information about and can be inverted for geoacoustic profiles. This was formulated as a Bayesian (probabilistic) inversion of measured BL data to estimate sound speed and density profiles (Holland et al., 2005). The results show the most probable depth-dependent sound speed and density profiles (**Figure 3**, *solid lines with solid circles*) with uncertainties (**Figure 3**, *dashed lines*).

Figure 3 also shows depth-dependent geoacoustic properties measured from two cores collected at the site, using specially designed corers to minimize sediment disturbance, which revealed the mud to be a nannofossil ooze. The agreement between the geoacoustic properties estimated remotely via AoI inversion and the core measurements is generally quite good, with a SSR = 0.976. It is clear that the AoI frequency dependence *does* contain significant information about the depth dependence of the mud properties.

A simple theory predicts that the minimum possible SSR value for mud is about 0.97. In other words, the minimum sound speed in mud is about 3% lower than that in seawater. Measurements over the last decades confirm this minimum value for muddy sediments with seawater in the interstices (the occasional presence of gas bubbles rather than water in muds can reduce the sound speed much more but is a story for another time).

A few percent variation in sound speed may seem hardly worth noting, but for ocean acoustic propagation, the effect can be considerable. In continental shelf areas, sound can travel long distances due to an acoustic waveguide formed between the sea surface and the seabed, given suitable seabed properties. For example, with sandy sediments, the sound speed is greater than that of water (SSR > 1), and a critical reflection angle exists at which the acoustic wave

Figure 3. *Estimated depth-dependent mud density (**left**) and sound speed (**right**) from an inversion of 300- to 1,600-Hz BL data south of Sicily, Italy, for the most probable geoacoustic profiles (**solid lines with solid circles**) and 95% credibility intervals (**dashed lines**). Properties measured from two cores (**dark and light crosses**) are also shown, with rough uncertainty estimates indicated as error bars. From Holland et al., 2005.*

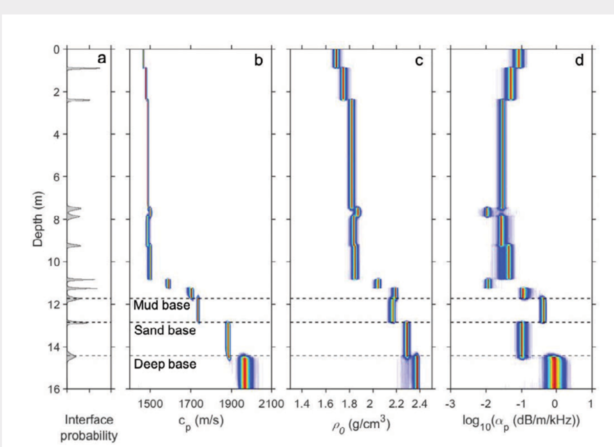


is completely reflected with no acoustic transmission into the seabed (typically at 15-30° grazing angle). In such cases, acoustic energy can propagate at angles below the critical angle with little loss to very long distances equivalent to hundreds of times the depth of the water.

However, for a muddy sediment with a SSR < 1, no critical angle (and therefore no acoustic waveguide) exists. Put another way, for a sediment with a SSR < 1, sound propagation in the ocean is limited to distances equivalent to only a few water depths. However, this rarely happens in practice at frequencies below 10 kHz for two main reasons. First, mud generally has a very low attenuation (compared with sands). Thus even for a mud layer tens of meters thick overlying sand, an acoustic waveguide often exists between the sea surface and the buried sand layer. Second, the mud sound speed can increase with depth such that there is a turning point within the mud where refraction bends the sound waves upward, returning acoustic energy to the water column. This is often the case in deep-water environments where muddy sediments can be many kilometers thick. Both reasons underscore the importance of understanding the depth dependence of sediment geoacoustic properties.

At the NEMP, 95 km south of Martha's Vineyard, Massachusetts, depth-dependent mud properties were inferred using reflection-coefficient data and Bayesian geoacoustic inversion (Jiang et al., 2023). The results are shown in **Figure 4**, plotted in terms of probability profiles for geoacoustic parameters. At this site, the mud thickness is found to be about 11.7 m. As is the case across the NEMP experimental area, a sand layer exists below the mud. The mud geoacoustic properties appear to fall into three depth intervals, upper 0-3 m, middle 3-10.8 m, and lower 10.8-11.7 m. The sound speed (**Figure 4b**) increases with depth in the upper interval, is nearly uniform in the middle, and exhibits an extremely large gradient in the lower.

Figure 4. *Depth dependence of geoacoustic properties at the NEMP from inversion of reflection-coefficient data. Probability profiles are shown for interface depth (**a**), sound speed (**b**), density (**c**), and attenuation (**d**). In these, the warm colors (e.g., **red**) indicate high probabilities and the cool colors (**blue**) low probabilities. The focus here is on the mud layer, above 11.7 m depth. From Jiang et al., 2023.*



When first observed, the high gradients in the lower mud interval were puzzling but have since been determined to arise from sand particles (from the sand layer below the mud) entrained in the mud by biologic (Nittrouer et al., 1986) and geologic (Goff et al., 2019) processes at the time the mud began to be deposited at the end of the last glaciation about 10,000 years ago. The fraction of sand increases with depth in the interval, which leads to the increase in sound speed. We term this lower interval the "transition interval" because it represents a gradual transition from mud to sand as opposed to a sudden change in sediment type.

Geoacoustic inversion results at two other sites at the NEMP, at 5 km and 19 km to the northwest with mud thicknesses of 10 m and 3 m, respectively, show remarkable similarity in the transition interval, its thickness, and sound speed gradient. This suggests that the geologic and biologic processes contributing to its formation were fairly uniform across the mud patch during the formation time. The other two sites also show similar depth dependence in the upper and middle intervals.

Attenuation

Attenuation is a challenging property to determine in sediments. Nevertheless, the inferred attenuation (**Figure 4d**) is sufficiently well determined (has small uncertainties) that we can discern its variation with depth. In the upper interval (0-3 m), attenuation decreases exponentially with depth (linearly in the log plot, smoothing through the stairsteps), is roughly constant in the middle interval, and increases rapidly in the lower (transition) interval. The large attenuation increase in the transition interval, nearly two orders of magnitude, is qualitatively understood to be due to the increasing sand content. At the two other sites at the NEMP (5 km and 19 km away), the attenuation exhibits a similar depth dependence. Recent core data at several locations near the site considered in **Figure 4** also show an exponentially decreasing attenuation in the upper layer at frequencies in the low hundreds of kilohertz.

The transition interval is controlled by biologic processes (e.g., mixing by benthic fauna) and geologic processes (sea level oscillations and sediment transport due to storms). Because these processes are virtually ubiquitous across the planet (e.g., Nittrouer et al., 1986), it seems likely that the transition interval may exist at all or, at least, at many muddy continental shelves. The characteristics of the transition interval are expected to vary depending on the regional processes. However, transition-interval characteristics may be approximately spatially uniform for a given shelf region. The transition interval and its similarity in a given region have been observed for the two continental shelf regions studied thus far in the North Atlantic and Mediterranean. Thus, if the sediment mixing and mud deposition rates are known for a given shelf, it may be possible to predict the transition interval thickness and geoacoustic characteristics and, hence, make better predictions of the depth-averaged attenuation in the mud layer. With improved geoacoustic properties, better predictions of the acoustic field in the ocean can be made, improving our ability to operate in and understand the ocean.

Frequency Dependence

The frequency dependencies of the sound speed and especially attenuation are important in understanding ocean-acoustic propagation in a particular environment. In theory, the attenuation can increase with frequency at rates varying from frequency to the one-half power to frequency squared, but the actual form of the frequency dependence for specific sediments is difficult to measure accurately. Nonetheless, it's quite important to measure because the change in attenuation with frequency over a few octaves can be dramatic.

There is growing evidence at the NEMP and other areas that muds with a modest sand content follow a nearly linear dependence of attenuation on frequency above a few tens of hertz up to at least 10 kHz. Furthermore, several observations (e.g., Yang and Jackson, 2020) have shown that mud sound speed shows little variation with frequency over from a few tens of hertz to hundreds of kilohertz. However, it should be noted that there are numerous other measurements of mud sound speed and attenuation, and there is not yet consensus as to the frequency and depth dependence of mud, even in the well-studied NEMP. **Figure 4** is meant to serve as an example of one set of results from a remote-sensing approach.

Models for Acoustic Propagation in Mud

Sediment-acoustic models are crucial for advancing our understating of mud acoustics. These models predict the wave speeds and attenuations as a function of frequency from a set of physical properties such as porosity. Carrying out geoacoustic measurements can be expensive, and if only a single measurement is available, say a core at 100 kHz, but a specific application requires a sound speed and/or attenuation at 100 Hz, models are required to bridge the spectral gap. More fundamentally, models provide a framework to test hypotheses and provide important constraints, for example, that the frequency dependencies of sound speed and attenuation are linked as a consequence of causality. Geoacoustic measurements and inferences, in turn, guide model development by providing observables that yield clues about the important underlying physics. Three sediment-acoustic models are currently used for muds; two of them have origins in models of wave propagation in granular media, whereas one was developed specifically for mud.

The mCreB model (Chotiros, 2021) is based on the Biot theory (Biot, 1962). Biot's original pioneering work involved modeling wave propagation through consolidated but porous media, such as rocks. This theory was subsequently modified over time to treat unconsolidated sediments. Most of the numerous subsequent Biot theory variants have been aimed at sands and silts, but a few treat mud. The most recent mud variant, mCreB, includes the mechanism of fluid flow ("squirt") at grain-to-grain contacts, developed for granular media, and adds mechanisms believed to be important for mud, including electrochemical forces binding a thin film of pore water to grain surfaces, the presence of tiny grains suspended in the pore water, and creep.

The viscous grain shearing (VGS) model (Buckingham, 2010) is based on a generalized Navier-Stokes equation (describing the motion of viscous fluids), invoking grain-to-grain sliding to introduce rigidity into the medium. The model has developed over several decades, motivated by modeling wave propagation through sandy sediments. However, in the last decade, it has been used for muddy sediments. Is that reasonable? The answer is possibly. VGS is a phenomenological model attempting to capture the complex physics of molecularly thin fluid films between sliding grains in terms of a Hookean spring and a time-dependent (strain-hardening) dashpot and time-independent dashpot (representing classical viscous loss) in series. Given the phenomenological approach, it is possible that the spring-dashpots model is useful for mud as well as for sand, even though the physics at the microscopic level may be quite different.

The silt-suspension theory (SST) (Pierce et al., 2017) considers mud composed of silt grains suspended in an effective fluid consisting of water and a matrix of clay particles. The clay particles are assumed to be arranged in a cardhouse structure (clay particles are electrically charged and can stick together face to edge, forming a so-called cardhouse structure). Although mCreB and GS are phenomenological models, SST attempts to work from first principles, including the electrostatic forces for clay and classical Stokes theory for the suspended silt. More recent work has invoked a continuous smear of relaxation processes that can be associated with diverse types of solid particles nominally in contact but sliding and separating in acoustic wave propagation.

Similarities exist between these models: strain hardening, creep, and relaxation processes are related. Differences also exist, of course, as evidenced by the differences in frequency dependencies predicted by the various models. However, a full discussion of model differences is beyond the scope of this article.

Still Muddy

There is still a lively debate about the properties of marine muds, including their depth and frequency dependencies. Furthermore, challenges remain in reconciling (1) remote measurements with each other, (2) direct measurements with each other, (3) remote and direct measurements, and (4) measurements with models.

Here is a minimal sampling of the outstanding questions being actively pursued in mud acoustics research.

(1) What are the key geologic, biologic, and chemical processes that lead to vertical and lateral variations in the geoacoustic properties of muds?

(2) What generalizations can be made for extrapolating findings for one muddy environment to other locations/mud types around the world?

(3) Do mud properties vary over time, for example, with seasonal changes in the seawater temperature (Wood et al., 2014)?

Acknowledgments

We gratefully acknowledge the support of the Office of Naval Research; our many colleagues who, like us, are fascinated by these questions; and helpful suggestions by *Acoustics Today* Editor Arthur Popper.

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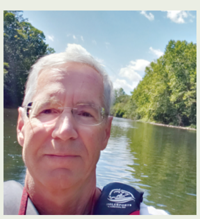

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What's It Like to Be a Bat? Ask Jim Simmons

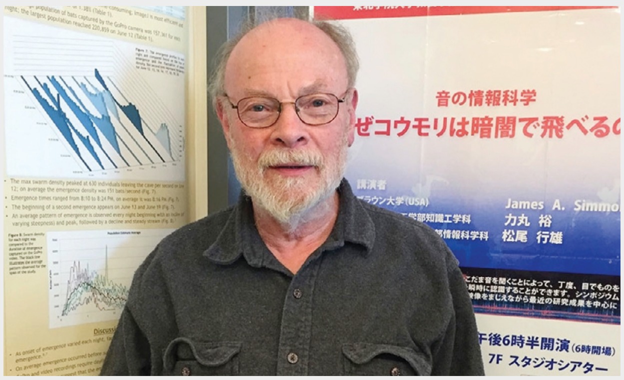
Cynthia F. Moss and Laura N. Kloepper

Imagine conducting research so groundbreaking that a team of international scientists convene a workshop titled Hard Data and Speculations to discuss your publications. This workshop lasts five days, focuses on an in-depth breakdown of your data, includes lively debate, and ends in an official signing of a declaration. Now imagine that the story of this declaration continues to be told to new generations of acousticians with whispers of awe. Who could be the great scientist behind this incredible legend?

"Pay no attention to the man behind the curtain," says James (Jim) Simmons (**Figure 1**) with a twinkle in his eye. This phrase is one of Jim's often-quipped taglines as he shows his bat laboratory and explains his research on the extraordinary sonar imaging of echolocating bats. For those who don't recognize this line, it comes from a scene in the motion picture *The Wizard of Oz* (see bit.ly/3vysQQA) when Dorothy's dog Toto reveals that a supernatural talking head is just an illusion created by a man operating a device behind a curtain.

This phrase has a double meaning to Jim. First, he uses the phrase to warn his audience about aspects of the bat's sonar imaging that may appear supernatural or beyond the grasp of human understanding. Second, Jim often conducts his research in his bat flight laboratory while hiding behind a curtain with his sophisticated electronic equipment. But don't let this jokester fool you; we should absolutely pay attention to the man behind the curtain because through his work on bat sonar imaging over the past six decades, Jim has revealed the extraordinary sensory capabilities of bats, developed sonar-processing models that are incorporated into bioinspired design, and touched the lives of countless students and colleagues who have been fortunate to know his work.

Figure 1. *Jim Simmons at a poster session in Japan in 2014. Photo by Laura N. Kloepper, reproduced with permission.*



The Discovery of Echolocation

Surprisingly, *so*und *na*vigation and *r*anging (SONAR) was an established technology nearly three decades before Galambos (1942) and Griffin (1958) demonstrated at Harvard University, Cambridge, Massachusetts, in the 1930s that bats produce ultrasonic calls and process echo returns with their ears. In the late eighteenth century, Spallanzani (1794) postulated that bats relied on sound to navigate, but at the time, there were no devices to formally test this idea, and human ears cannot detect the ultrasonic cries of bats. Spallanzani conducted experiments that separately eliminated the bat's use of vision, touch, and hearing to explore the relative importance of these senses to its navigation. He found that interfering with the bat's hearing had the most detrimental effects on navigation, but the sensory information these animals used to avoid obstacles and capture prey remained a mystery. More than a century later, with the use of specialized equipment provided by G. W. Pierce, a physics professor at Harvard University, Griffin and Galambos (1941) demonstrated that bats could steer around fine wires and discriminate edible and inedible targets by producing ultrasonic calls and listening to echoes from objects in the surroundings. They also showed that taping the bat's mouth closed or plugging its ears interfered with its ability to navigate. Griffin (1944, 1958) coined this remarkable active sensing behavior, echolocation. The reader can find modern reviews of bat

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echolocation in *Acoustics Today* (Simmons, 2017) and volumes of the *Springer Handbook of Auditory Research* (*SHAR*) series, such as *Hearing by Bats* (Popper and Fay, 1995), *Biosonar* (Surlykke et al., 2014), and *Bat Bioacoustics* (Fenton et al., 2016).

Graduate Training at Princeton University

After completing his undergraduate degree in psychology and chemistry in 1965 at Lafayette College, Easton, Pennsylvania, Jim launched his scientific career as a graduate student (1965–1969) at Princeton University, Princeton, New Jersey, in the laboratory of Ernest Glen Wever (see acousticstoday.org/7408-2), a renowned auditory scientist whose research program explored mechanisms of hearing in a wide range of species. Graduate students in Wever's laboratory during Jim's tenure at Princeton University studied a variety of organisms, including fish (Richard R. Fay), cats (James Saunders), and dolphins (James McCormick). Wever also hosted many senior scientists and visitors who contributed to a vibrant interdisciplinary laboratory environment. In an era when audio technology was in its infancy, Wever made connections with Bell Telephone Laboratories researchers, who provided state-of-the art equipment for the measurement and analysis of sound. This equipment, along with custom devices, was essential to the success of Jim's doctoral research.

As a graduate student, Jim learned that Wever had a colony of bats waiting for a research question, and he decided to unravel the mysteries of echolocation in these animals. Such experiments would take tremendous creativity and perseverance, and Jim rose to the challenge. Jim adapted classic psychoacoustic methods to measure range difference discrimination thresholds in bats. The success of these experiments depended on Jim's astute observations of bat natural behaviors. He designed a task that required a bat to fly or crawl toward a trained stimulus. Jim presented the bat with two objects, one closer and one further away and rewarded the bat with a tasty insect for approaching the closer object. He gradually decreased the difference in distance between the two objects and determined the minimum range difference that bats could reliably discriminate (see ***Target Range Discrimination Experiments***). Researchers around the world have since adopted Jim's behavioral methods to address a wide range of scientific questions on sonar perception in bats.

Important Visitors to Wever's Laboratory at Princeton

At the time Jim was conducting his thesis research, spatial perception by echolocation was not well understood, and one of the exciting moments of his graduate career came when a skeptical Nobel Laureate, Georg von Békésy (see acousticstoday.org/7302-2), traveled from Harvard University to visit Wever's laboratory at Princeton University. von Békésy (1960), who made important and fundamental discoveries about the transduction of sound in the inner ear, did not believe that the bat auditory system operated fast enough to support echolocation. Griffin, who was already greatly impressed by Jim's research, took the train from The Rockefeller University, New York, New York, to Princeton University in a plot to quash von Békésy's doubts about bat biosonar. Jim's demonstrations of his behavioral research methods and bat sonar range discrimination performance curves convinced von Békésy not only that the bat auditory system operated on a fast enough timescale to use echolocation for navigation but also to estimate target distance from echo delay. It was not until some years later that Jim found out that this exchange was a setup. Wever and Griffin both knew the significance of Jim's discoveries and wanted von Békésy to see Jim's work firsthand. Jim's trailblazing dissertation *Perception of Target Distance by Echolocating Bats* demonstrated the extraordinary abilities of bats to determine target distance from the delay of echo returns (see Simmons, 1973) and laid the foundation for decades of sophisticated behavioral studies of animal sonar in air and underwater.

Not all visitors to Wever's laboratory were scientists. One noteworthy visitor during Jim's time at Princeton University was the philosopher Thomas Nagel (see bit.ly/3HeKrzt), who later went on to publish his famous essay, "What Is It Like to Be a Bat?" In his essay, Nagel (1974) used the example of a bat to make his argument that the subjective mind of another cannot be accessed. In the era when Jim met Nagel, the scientific community shunned any notions that one might consider the mental state or consciousness of an animal, but psychophysical measurements relating the physical dimensions of a stimulus and animal performance were considered objective and rigorous. In this vein, Jim took a scientific approach to shed light on the images represented in the bat's sonar receiver. Was Jim's work inspiration for Nagel's essay? One will never be certain, but

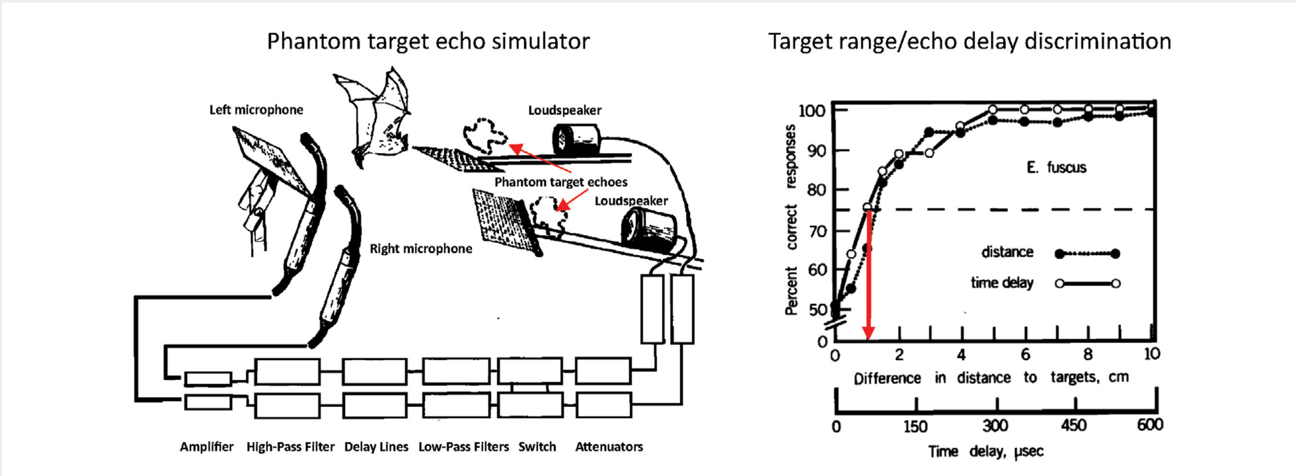


Figure 2. ***Left:*** *methods used to simulate echoes at different delays. The bat produced echolocation calls, which were picked up by microphones to its left and right. The signals were amplified, filtered, delayed, and played back through loudspeakers to generate phantom target echoes. The bat was trained in a two-alternative forced-choice procedure to approach the closer phantom target, i.e., playback echoes with the shorter delay, for a food reward.* ***Right:*** *comparison of the bat's performance (percent correct) in discriminating the difference in distance of two physical targets (**solid circles, dotted line**) and the echo delay of two phantom targets (**open circles, solid line**).* ***Vertical red arrow:*** *range difference (~1 cm) or echo delay difference (~ 60 µs) yielding 75% correct performance. The alignment of the two performance curves for physical object distance and playback echo delay discrimination demonstrates that bats use echo delay to determine target distance. Figures from Simmons, 1973.*

the timing of Nagel's visit, five years prior to his published essay, raises the intriguing possibility.

Jim's Work Leading to the Declaration of Sandbjerg

Target Range Discrimination Experiments

At the time Jim began his experiments on sonar ranging in bats, there were competing theories on the acoustic cues bats use to measure distance. Pye (1961) proposed that bats relied on beat frequencies that arise from overlap between outgoing sonar calls and returning echoes to determine target distance; however, Cahlander et al. (1964) reported that the frequency-modulated (FM) calls produced by insectivorous bats rarely overlap with returning echoes, thus debunking the beat theory of sonar ranging.

Jim's psychophysical experiments provided conclusive evidence in support of the hypothesis that bats use the time delay between sonar call and echo to measure target distance. He showed this through careful two-alternative forced choice (2AFC) psychophysical experiments that required the bat to discriminate between the arrival time of two electronically delayed playbacks of the animal's sonar calls, "phantom target" echoes. Jim discovered that the bat's performance depended on the echo delay difference between two playback echoes, showing almost 100% correct choices for delay differences greater than 300 µs and falling to chance for delay differences of 0 (**Figure 2**). Jim also demonstrated that bats could discriminate echo delay differences as small as 60 µs, which corresponds to range differences of approximately 1 cm. Importantly, he did these experiments with both phantom and physical targets to further test the notion that bats rely on echo delay to measure target distance.

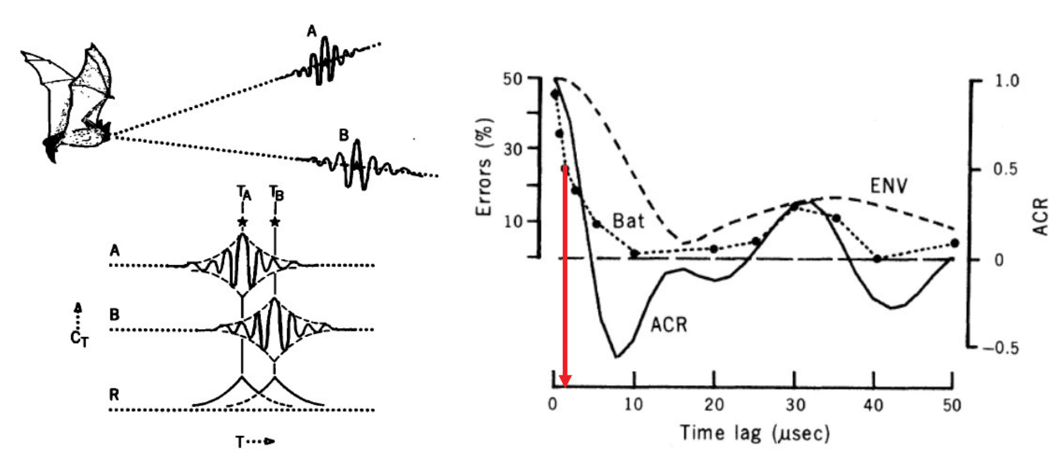
Further experiments carried out by Jim showed that a bat's ranging performance depended on the bandwidth of its echolocation signals. Again, using psychophysical approaches, he explored the echo delay discrimination abilities in four different species of bats that use echolocation signals with varying bandwidth (Simmons, 1973). Jim found that bats using broadband echolocation signals, such as the big brown bat *Eptesicus fuscus*, show finer range discrimination performance than bats that use narrowband echolocation signals, such as the greater horseshoe bat *Rhinolophus ferrumequinum*. These comparative data were consistent with Jim's hypothesis that bats perceive target distance by cross-correlating the outgoing call and returning echo, yielding a time-domain readout of target range or echo arrival time from the envelope of the correlation function. This is referred to as a matched filter operation, whereby the arrival time of returning echoes is measured from the peak of the cross-correlation function (see Woodward, 1953).

This matched filter operation can take the form of a semicoherent or coherent ideal receiver. A semicoherent ideal receiver encodes the envelope of the cross-correlation function, and a coherent ideal receiver encodes the fine structure (phase) of the cross-correlation function (for more explanation, see Simmons and Stein, 1980; Skolnik, 2002). Jim noted that the cross-correlation functions of broadband echolocation signals show a sharper peak in time than those of narrowband echolocation signals, and the bats' range discrimination performance curves parallel the envelope of their species-specific sonar correlation functions. These observations led Jim to posit in his 1973 paper that bats operate as semicoherent ideal receivers.

Microsecond Discrimination of Jitter in Echo Delay

Jim also observed that the bats made head movements when performing the 2AFC range difference discrimination tasks and hypothesized that head movements could smear the bat's perception of target distance. Without the influence of head movements on range discrimination, perhaps bats would show greater performance and potentially reveal that they operate as ideal coherent receivers. Jim came up with a new experimental paradigm that asked the bat to measure target distance (or echo delay) without moving its head. This task required the bat to discriminate between echoes that alternated in delay between successive echoes (a jittering target) from echoes that returned at consistent delays (a stationary target). The comparable experiment for a human would be to discriminate between dots at a fixed distance and dots that alternate between two distances, separated by millimeters or even micrometers. The results showed that bats could discriminate changes in echo delay of less than 1 μs, corresponding to a change in distance in the micrometer range.

Figure 3. ***Left:*** *relationship between the positions of targets in range (or delay) and the location of the central peaks in the cross-correlation functions for outgoing sounds and returning echoes for two targets, A and B, at different distances from the bat. This schematic is intended to provide the reader with an intuitive understanding of Simmons's interpretation of sonar ranging by bats, i.e., the animal cross-correlates its sonar call and returning echo to estimate echo delay.* T_A*, time of arrival of echo A;* T_B*, time of arrival of echo B following the operation of a receiver (R). From Simmons, 1973.* ***Right:*** *jitter discrimination task required the bat to differentiate between two playback stimuli, one containing echoes that alternated in delay (a jittering target) and one containing echoes that returned at stable delays (a stationary target). Jitter values ranged from 0 to 50 μs. The bat's percentage errors were plotted as a function of the jitter in echo delay (time lag) in microseconds. Note that the bat in this task successfully discriminated jitter in echo delay on the order of 1 μs, referencing a 75% correct (25% error) criterion (vertical red arrow).* ***Dotted line:*** *envelope of the autocorrelation function (ENV);* ***solid line:*** *fine structure of the autocorrelation function (ACR). Note that the rise in errors at 30 μs corresponds to the sidelobe of the fine structure of the correlation function. Because the bat's performance aligns with the fine structure of the correlation function, Simmons argues that bats perceive the phase of echo returns and hence operate as ideal sonar receivers. From Simmons, 1979.*



Furthermore, bats showed a rise in errors at around 30 μs. These findings led Jim to infer that the echolocating bat operates as a coherent ideal sonar receiver that represents the fine structure (phase) of the time-domain representation of target distance. In this scenario, the bat measures target distance from the peak of the correlation function along the delay axis (**Figure 3**) but is also sensitive to interference from sidelobes. In the jitter discrimination experiment, the bat appeared to sometimes confuse the central peak of the correlation function with the sidelobe when the echo delay alternated by 30 μs. In other words, Jim posited that the bat did not reliably discriminate 30-μs jitter in echo delay because it is sensitive to the fine structure (phase) of the correlation function, occasionally confusing the central peak and the sidelobe. Interested readers are referred to Skolnik (2002) for more background on sonar receivers.

Jim's stunning report that bats discriminate jitter in echo delay of less than 1 μs and show sensitivity to the phase of the correlation function was published in *Science* (Simmons, 1979). These findings and their interpretation that the bat operates as an ideal sonar receiver stirred a great debate among scientists in the field (see the controversial paper by Beedholm and Møhl, 1998), largely because coding of phase in the auditory system is believed to be limited to sound frequencies below 5 kHz, not in the ultrasound range used by bats. For readers who would like to learn more, Jim published a review in *Acoustics Today* (Simmons, 2017).

Replication of Jitter Discrimination Experiments

Among those who challenged the interpretation of Jim's 1979 jitter discrimination data was Hans-Ulrich (Uli) Schnitzler. Uli argued that there are strict criteria for specifying the operation of an ideal sonar receiver and the shape of the psychophysical performance curve cannot substitute for these criteria (see Skolnik, 2002). He also noted that the analog delay lines that were used to generate microsecond jitter in echo arrival times could have generated spectral cues rather than echo delay for the bats to perform the discrimination task (see Moss and Schnitzler, 1995). Uli arranged for his electronics shop to build a digital delay line to replicate Jim's experiments, eliminating the possibility of spectral artifacts. Experiments in Uli's laboratory confirmed that bats can indeed discriminate jitter in echo arrival time of less than 1 μs (Moss and Schnitzler, 1989).

Uli and his colleagues at the University of Tübingen, Tübingen, Germany, then went on to demonstrate with the same apparatus that bats can discriminate the phase of echo returns (Menne et al., 1989). Because these experiments were conducted with a digital delay line, the spectral artifact criticism associated with analog delay lines could be tossed aside, but these latter experiments yielded jitter discrimination performance curves that differed from those in Jim's 1979 report. Namely, the rise in range discrimination errors at 30 μs was absent in the data from Uli's laboratory. The source of this discrepancy in data from the two laboratories remains a

Figure 4. *Bat's performance detecting jitter in the delay of playback echoes. The bat produced echolocation calls, which were picked up by two microphones, electronically delayed, and played back through two loudspeakers, one placed to the left and the other to right of the bat's observation position. On each trial, one loudspeaker returned echoes at a fixed delay and the other loudspeaker returned echoes that alternated in delay from one broadcast to the next, simulating a target that jittered in range. The jittering target was randomly presented through the left or right loudspeaker on successive trials, and the bat was rewarded for crawling toward the jittering target. In this experiment, jitter ranged from 0 to 60 ns, more than an order of magnitude smaller than the jitter values tested in Simmons' (1979) experiment. The bat's performance ranged from ~50% (chance) in control trials with 0 ns jitter to ~90% correct with jitter values greater than 20 ns. Jitter in echo delay was produced in two ways, using either an analog delay line or cables of different lengths. Note that in this experiment, the bat's jitter discrimination threshold was about 10 ns (**vertical red arrow**), referencing a 75% correct performance criterion. From Simmons et al., 1990.*

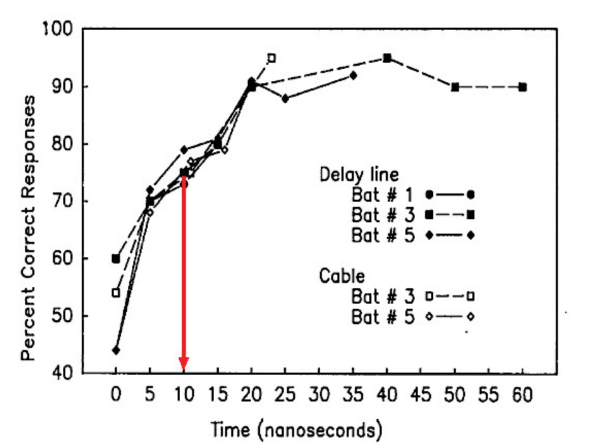


Figure 5. ***Left:*** *signing the Declaration of Sandbjerg in Sønderborg, Denmark, in 1994. Photo of (****left to right****) Cynthia F. Moss, Johns Hopkins University, Baltimore, Maryland; Hans-Ulrich Schnitzler, University of Tübingen, Tübingen, Germany; James Simmons, Brown University, Providence, Rhode Island; and Lee Miller, University of Southern Denmark Odense, Denmark,* ***Right:*** *Jim Simmons signed the declaration,* Under the assumption that in a jitter experiment a bat compensates for all errors caused by its own movements during the measuring process, the 40-ns threshold obtained at a 36 dB S/N ratio can be understood ONLY on the basis of a coherent receiver. *All others who signed below were witnesses. Photo by Annemarie Surlykke, University of Southern Denmark Odense, Denmark, reproduced with permission.*

mystery today, but Jim and Uli appreciate each other as scientists and colleagues. They are always happy to have a beer together after an intense scientific debate.

Nanosecond Discrimination of Jitter in Echo Delay and the Declaration of Sandbjerg

Jim continued to measure sonar jitter discrimination thresholds and reported that big brown bats can discriminate echo delay changes on the order of 10 ns (**Figure 4**) (Simmons et al., 1990). This astonishing result sparked further debate, and in 1994, Uli Schnitzler, Annemarie Surlykke, Bertel Møhl, Lee Miller, and Cindy Moss organized a workshop to explore the scientific issues. The workshop, titled Spatial Perception in Echolocating Bats: Hard Data and Speculations, took place over 5 days at Sandbjerg Manor, Sønderborg, Denmark. Each day consisted of multihour discussion sessions of papers (largely from Jim's laboratory) and written summaries of discussion.

The workshop concluded with a signing of the Declaration of Sandbjerg that states *Under the assumption that in a jitter experiment a bat compensates for all errors caused by its own movements during the measuring process, the 40-ns threshold obtained at a 36 dB S/N ratio can be understood ONLY on the basis of a coherent receiver*. Jim undersigned this statement (see **Figure 5**). Although the scientific issues were far from resolved after this meeting, the discussion was stimulating and spirits were high. Over the years since this workshop, researchers have continued to argue these points and mostly agree to disagree.

Jim's Additional Contributions to Knowledge of Bat Echolocation

Along with Jim's fundamental contributions to our understanding of bat perception by sonar that led to the Declaration of Sandbjerg, he also conducted groundbreaking neurophysiological experiments in echolocating bats soon after he began his first faculty position in the Psychology Department at Washington University, St. Louis, Missouri. Also at Washington University at the same time was the renowned auditory physiologist and former postdoc of Donald Griffin, Nobuo Suga (see **Figure 6**).

Range-Tuned Neurons

Discussions with Griffin and Suga inspired Jim to probe the neurophysiological underpinnings of echo ranging in bats, and his 1978 paper with coauthors Albert Feng and Shelley Kick led the way for decades of research on this problem (Feng et al., 1978). Feng et al. described

Figure 6. *Photo of (**left to right**) James Simmons, featured in this article; Donald Griffin, the modern-day discoverer of echolocation in bats; and Nobuo Suga, an eminent auditory neurophysiologist, taken at Washington University, St. Louis, Missouri, in the 1970s. Photo by a student in the laboratory, used with permission from James Simmons.*

the response properties of auditory neurons in the bat midbrain intercollicular nucleus that exhibit the response characteristic known as "echo delay tuning" or "range tuning," which may serve as the neural substrate for target distance coding. Echo delay-tuned neurons show little or no response to single sounds but show facilitated responses to pairs of sounds, simulating echolocation calls and echoes, separated by a restricted range of time delays. This remarkable discovery sparked decades of research in bat auditory neurophysiology. Echo delay-tuned neurons in the bat brain have since been identified in many other stations of the auditory pathway in passively listening bats (reviewed by Covey, 2005; Ulanovsky and Moss, 2008; Suga, 2015; Wohlgemuth et al., 2016). Only recently have experimental methods advanced to show that neurons in the bat midbrain superior colliculus encode the three-dimensional (3D) location of physical objects by responding to echoes from calls produced by the actively echolocating bat (Kothari et al., 2018).

Sonar Gain Control

Jim also made the fundamental discovery that bat sonar exhibits an automatic gain control in which the bat's auditory system changes sensitivity according to the delay of the receiving echo, and this adjustment serves to stabilize the perception of echo amplitude over changing distance. Using psychophysical methods, Jim observed that the hearing sensitivity of the big brown bat (*Eptesicus fuscus*) decreases before each sonar pulse is emitted and then recovers in a logarithmic fashion to compensate for the two-way transmission loss of sonar returns, thereby stabilizing the bat's estimate of echo arrival time, which is the bat's cue for target distance (Kick and Simmons, 1984; Simmons et al., 1992). Early experiments required the bat to detect spheres presented at different distances and revealed that the detection threshold increased with a decreasing target distance over a range of about 1.5 m (Kick, 1982). Later experiments transmitted playbacks of the bat's calls to simulate echoes from objects at different distances (Simmons et al., 1992). The playback experiments showed the same trend, a change in threshold with echo delay, corresponding to target distance. The bat's gain control is key to its extraordinary sonar-ranging performance and has important implications for applications in sonar technology. It has also been demonstrated in echolocating marine mammals (Au and Benoit-Bird, 2003).

Acoustic Clutter Rejection

Jim's research has also offered insight to the ways echolocating bats deal with acoustic clutter. When a bat is seeking insect prey in the vicinity of vegetation, each sonar call returns echoes from the target of interest along with a stream of echoes from branches, leaves, and other objects in the vicinity. A study Jim conducted with collaborators at Doshisha University, Kyoto, Japan, led to the discovery that FM bats operating in dense clutter shift the spectral content of successive sonar calls to tag individual returns within echo streams (Hiryu et al., 2010). In this scenario, one echo stream overlaps with the next and the bat's frequency adjustments to its sonar emissions serve to ensure accurate call-echo assignment, which is needed to measure object distances in complex environments. Additional experiments from Jim's laboratory suggest that the directional characteristics of the bat's echolocation calls and its hearing may serve to mitigate clutter interference. They posit that off-axis echoes may be perceived by the bat as "blurry" due to the frequency-dependent directionality of sonar signals and the dependence of auditory-response latencies on echo amplitude. Because bats point their sonar directly at selected targets where echo returns are the strongest and sharpest, blurry object echoes off to the side would not interrupt processing of the selected target along the midline (Bates et al., 2011).

Figure 7. ***Left:*** *Jim Simmons delivering his lecture at the Pioneers in Echolocation session at the Active Sensing Meeting at the Weizmann Institute of Science in Rehovot, Israel, in January 2023. Photo by Cynthia F. Moss, reproduced with permission.* ***Right:*** *Pioneers of Echolocation (**left to right**): Jim Simmons, Uli Schnitzler, and Alan Grinnell. Photo by Annette Denzinger, reproduced with permission.*

Jim Today

Jim, today in his 80s, remains active in science. In January 2023, Jim was recognized in a special Pioneers in Echolocation session of an international meeting on Active Sensing, held at the Weizmann Institute of Science, Rehovot, Israel (**Figure 7**). There, he enjoyed lively discussions with his scientific challenger Uli Schnitzler and long-time colleague and former graduate student of Donald Griffin, Alan Grinnell.

Jim has a long history of supporting students and early-career researchers, both through formal and informal mentoring. He has made several extended visits to Japan where he mentored students and collaborated with faculty on animal bioacoustics research. Some Japanese students and colleagues traveled to Providence, Rhode Island, to wrap up their projects in Jim's laboratory at Brown University.

Jim's knowledge and enthusiasm for bats is infectious, and his impact can be summed up by the quotation from Uli: "Jim Simmons has provoked me to think more than any other individual in the field."

Jim is an avid reader of history and enjoys the outdoors, particularly field expeditions to listen in on bat activity. He collaborates on research with his wife Andrea, and the two have published over 20 papers together. They are proud parents of Jessica and Ryan and grandparents of six-year-old AJ.

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Large-Venue Acoustics: Arenas, Stadiums, and Amphitheaters

Gary W. Siebein, Keely Siebein, Jack Wrightson, Joe Solway, and Raj Patel

Introduction

There are many unique aspects to the acoustics of large venues in cities and towns in the United States and around the world where sporting events, large social gatherings, concerts, special events, and other activities occur. These spaces have large audiences, large buildings, sophisticated audio systems, and often loud sounds associated with their use. Such spaces include arenas, large event spaces, stadiums, amphitheaters, and other large spaces that may accommodate several thousand to over 100,000 people. Seating, egress, and access for these numbers of people require large floor areas even when multiple levels of seating are used. Many of these facilities are fully or partially enclosed. The room volume becomes quite large due to the height required to get as many people as possible as close to the stage or sporting field as possible and yet not obstruct the flight path of balls in a sports stadium. Indeed, the acoustics of large venues are very different, and often more complex, than for smaller single-use venues because of the large volumes, variability in size and configuration, and their multiple types of usage. This article focuses on the unique acoustics of these very large spaces.

Acoustical Issues in Large Venues

Speech Clarity and Bass Sounds

A major issue for large venues is that there is often a need for clarity of speech for announcements, emergency evacuation instructions, and play-by-play descriptions of sporting events. Careful design of loudspeaker systems and strategically located sound-absorbent materials are used to address this issue. In fact, to ensure clarity of speech, design schemes for the facilities are studied in three-dimensional computer models where the shape, materials, and sound system are iteratively developed to fine tune their combined performance to optimize the intelligibility of sounds over the audience seating areas. Simultaneously, there is a need for loud, high-energy sound with a strong low-frequency or bass component for amplified performances in these venues. These sounds present acoustical challenges for sound within the facility such as providing enough lower frequency absorption to reduce the resonant buildup of sounds. Indeed, by including a large venue within a complex of buildings with other uses such as residential, dining, other entertainment, and hospitality near the entertainment venue provides even greater acoustical challenges to control sounds emitted out of the facility.

Home Field Advantage

In spaces where both sporting events and large concerts are held, many guests enjoy the reflected and reverberant buildup of crowd sounds often called the "home field advantage." This means that a balance must be created between the clarity of speech and music sounds and the passive reinforcement of cheering by guests to keep the space lively. Thus, the ceiling and wall elements are shaped to provide reflective reinforcement of sounds made by the crowds that reaches out to others in the crowd as well as players on the field.

Building Services

When the spaces are partially or fully enclosed, large air-conditioning systems are required. Thus, a noise- and vibration-control design is needed to reduce the sounds from the air-conditioning equipment that are propagated into the facility and limit off-site noise propagation from the building to adjacent properties.

Audio and Video Systems

The design and control of audio, video, broadcast, and technical communication systems in these buildings is a complicated exercise involving multiple design team members because achieving uniform sound coverage

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from loudspeaker systems with adequate clarity and full-frequency response is often challenging due to the large seating areas and geometry of the venues. Furthermore, the design of viewing systems, including large scoreboards with video displays, must account for viewing angles for all members of the audience who are spread over very large areas. Control of ambient light in outdoor venues can help improve the visibility of the screens. In addition to the house systems, rental and touring systems are often used in these venues, further complicating the audiovisual (AV) system design and operation.

Sound Emissions

Large venues are often constructed in or near built-up areas so that a large population base has access to the facility. However, this means that sound-sensitive neighbors may be located close to the facility. To deal with this, iterative studies of sound propagation from the facility are often done during design to understand how the sounds from the facility may impact the surrounding community. This often involves three-dimensional computer models of the facility with the sound system loudspeakers and the shape, materials, and design features of the buildings and the surrounding buildings are constructed as part of the process.

Municipalities may also have special entertainment sound regulations. The use of sound-monitoring systems during live events is often included in the design and operation of the venue, enabling the facility operators to know how loud the sounds are at locations in the community to help avoid situations where the sounds exceed local regulatory limits.

Health Concerns

Although many people enjoy the experience of listening to events with high sound levels and the thrill of crowd responses at sporting events and concerts, these levels also bring concerns for sound-related health effects. These include temporary and permanent threshold shifts and possibly hearing loss as well as physiological effects including high blood pressure and circulatory and respiratory effects among others. Many concert venues include warnings and disclaimers at the venue and as part of the ticket purchase in acknowledgment of the potential health hazards. Indeed, the 2018 Environmental Noise Guidelines by the World Health Organization (WHO; see bit.ly/3sODnWW) has recommendations for limiting recreational sound exposure and is encouraging additional research on the health effects of high-level entertainment sounds on audience members and working staff due to the transient nature of the exposure.

Outdoor Music Venues

Precedents

Ancient Greek and Roman amphitheaters with a raised stage a stepped, semicircular seating area set into the topography, and a natural acoustic sonic projection to a large audience is a prototypical typology for the outdoor music venues of today. More recently, bandstands were built in many communities for nonamplified sound sources such as a local band or performance group. Sometimes, a small sound system consisting of a microphone and one or two loudspeakers on stands would be used so an announcer or single performer could be heard at greater distances from the bandstand.

Acoustical Design Issues

The historic precedent of the bandstand on the village green has been transformed into facilities with larger audiences, higher power sound and video systems, and more frequent uses in many communities. Thus, the architectural acoustic design of these venues was significantly changed by the transition from natural acoustic sound propagation to completely amplified sound to accommodate larger audiences and higher sound levels. As the venues grew, acoustic issues changed to provide the most effective sound experience for the audience.

Related to the size of the venue, another issue that arose as venues got larger is that many facilities host a wide variety of performance types. These range from community orchestras and meetings to large touring groups and multiday festivals with large line array loudspeaker systems and rows of subwoofers for a wide variety of lively modern music genres.

Passive and active variable acoustic systems can be employed to adjust the acoustics for different types of performances and sizes of audiences in these venues. For a small venue, active systems may include electronic architecture systems that have a network of loudspeakers located over the stage and throughout the venue to add reflections on the stage so that orchestra members can hear each other. Reflective and reverberant enhancements can also be added to sounds heard by the audience. Adjustable acoustical elements can include moveable sound-absorbent, reflective, and diffusive panels on the walls and roofs of the facility and adjustable stage floors among others. Small outdoor performance venues may have a permanent stage with an angled or curved roof to provide hang points for rental lighting, audio, and video systems and for poles along the perimeter of the seating area for delay loudspeakers to serve the outer seating areas for larger events. A back-of-house building can be used to shield adjacent homes from sounds.

A medium-sized outdoor performance venue may have a stage in a permanent structure, with structural hang points to hold large video displays and line array loudspeakers. The stage is often lined with perforated-metal sound-absorbing panels so that sounds from the monitor loudspeakers used by the performers on stage so that they can hear each other do not reflect back to the audience. The facility can also have large doors that can be opened on the front and back during warmer weather for views and to allow breezes to blow through the facility but that can be closed when not in use to protect equipment stored in the building. Poles for delay-ring loudspeakers used during larger events are located around a paved ring around the perimeter of the seating area. There is often no fixed seating, but instead, the audience brings lawn chairs and blankets to enjoy the performances in a relaxed atmosphere.

A large amphitheater with 4,000 folding seats under the canopy and room for an additional 5,000 to 10,000 people or more on the lawn and other surrounding areas in a medium-sized city is shown in **Figure 1**. The canopy has a sound-absorbing inner liner to reduce reverberant sound buildup under the roof. The curves of the roof were carefully designed to minimize sound focusing for the audience and performers, whereas the vertical walls in the stage area are lined with thick sound-absorbent panels to reduce sound reflections to the audience. The main loudspeaker arrays, monitor loudspeakers, video displays, and control consoles are rental or touring company equipment. Delay-ring loudspeakers are part of the permanent equipment at the facility. A sound-monitoring system was included as part of the operational plan for the facility.

Figure 1. *Large amphitheater with a covered roof and open lawn seating area.*

Domed Stadium Community Noise and Room Acoustics Considerations

Indoor stadiums present acoustical challenges that are different from more typical spaces when considered at the scale of a 65,000 to 100,000+ seat capacity. The primary concern is how the building materials affect the inside-to-outside sound transmission. Most stadiums feature relatively lightweight construction outboard of a concrete structural frame and seating risers. The exterior skin can feature a significant amount of glazing and/or lighter weight curtain wall construction that provides minimal sound transmission loss at the low frequencies that are part of modern popular music.

From a noise control perspective, typical community concerns apply, such as outdoor mechanical-plant noise levels and, more importantly, sounds from amplified music concerts held inside the stadium propagating to neighboring properties. The concert sound levels are not necessarily higher than at other concert venues. However, the total sound power can be higher due to the combination of sounds from the main loudspeakers at the stage and supplemental "delay/fill" loudspeakers employed by some productions to cover remote seating areas and hard to reach locations in the corners of the facility. In addition, loudspeakers that are located away from the stage must have digital delays added to the signals to slow down or delay the sounds played through them so that the delayed sounds arrive correctly aligned in time, slightly after the sounds traveling directly from the stage. This is because the sounds traveling through wires, unless delayed, will reach audience members before the sounds from the stage that are traveling through the air. The house sound system may also be used to cover some seating areas.

More importantly, the roof construction can feature even lower mass than the exterior walls, with metal roof decks with rigid foam insulation and single-ply rubber roofing

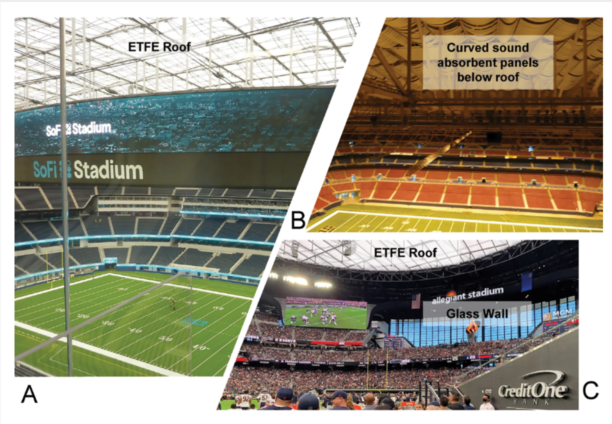

Figure 2. *Stadium roof systems.* ***A:*** *SoFi Stadium in Inglewood, California, setup for American football with an ethylene tetrafluoroethylene (ETFE) roof system.* ***B:*** *dome at America's Center in St. Louis, Missouri, that has a conventional roof with suspended baffles for acoustical treatment.* ***C:*** *Allegiant Stadium near Las Vegas, Nevada, that has a moving glass end wall and ETFE roof.*

materials or even lower mass, translucent ethylene tetrafluoroethylene (ETFE) plastic roofing systems (**Figure 2**). ETFE panels can be a single layer supported at the ends or a double panel with a pressurized airspace between the two panels. One advantage of the relatively lightweight construction is that the effective low-frequency absorption is substantial for the roof, and especially for the ETFE sections, because the low frequencies simply pass through.

Furthermore, typical, air-pressurized ETFE roofs are highly reflective at speech frequencies, and the pressurized cells have a drumhead resonance that is audible when hundreds of the same-sized cells are vibrating at the same frequencies. Suggestions to stagger the size of the ETFE cells to reduce the resonance have been rejected by structural engineers not wanting to add complexity and cost to the support systems.

The ETFE roofing systems weigh around 1.46472 kg/m^2 (0.3 lb/ft^2) excluding the support framing and primary building structure, with transmission loss values of 6 dB or less in the 200-Hz and lower octave bands. In addition to the roof having the lowest overall transmission loss of the building exterior elements, it is also the single largest surface, so the radiation of sound through the roof can be the most significant component of the noise traveling to adjacent properties, especially if they are elevated and have a line of sight to the stadium roof. Where local noise ordinances have C-weighted or octave-band sound level limits, it can be hard for a concert event to comply with sensitive nearby neighbors without either interior noise level limits on the performers or additional mitigation in the building structure. Full or partial ETFE roofs are featured in recently built stadiums in Minneapolis, Minnesota; Los Angeles, California (**Figure 2A**); and Atlanta, Georgia, the latter also having some ETFE exterior wall area, and for a proposed facility in Nashville, Tennessee.

Room Acoustics

Clearly, the room acoustics of domed stadiums are notoriously difficult and, at first experience, confusing. When a small group of people meet at the periphery of the field speaking in relatively low-level sounds, the space behaves as if it were an outdoor stadium. This is because the sound source (the people) does not fully excite the space and because the reflective surfaces are so far away that distance loss reduces the sound levels to a point where they aren't heard as echoes. However, with very loud sounds, such as a high-energy, amplified concert or a large crowd cheering during a sporting event, the domed stadium can have a very reverberant character, with significant echoes.

This dichotomy in the acoustics of the stadium between when it is empty with just a few people speaking and when it is fully occupied with an active crowd is due to the combination of the very large interior space of the stadium and the materials used to construct and finish the bowl-shaped seating area, which is among the largest single volume interior spaces in the world. The scale of these spaces is large enough that the traditional methods of calculating and measuring reverberation tend to fall apart because the acoustical energy required to create a homogenous sound field in the spaces is larger than one might expect and the distances that sound travels from a source to many reflecting surfaces are impacted by distance loss/air absorption. For this reason, conventional reverberation time (RT or $T60$) calculations tend to overestimate the reverberation time and a correction for spaces with a mean free path of over 61 m (200 ft) has been suggested (Wrightson and Johnson, 1994).

Early measurements in the Houston Astrodome, Houston, Texas, with a small interior volume compared to more recent domed stadiums, often used yachting cannons and other firearms firing blank cartridges as sound sources for making acoustical measurements. Even these loud sources often resulted in simply measuring the decay of the reflections rather than the complete reverberant sound decay because the space was not fully excited by the source sound. This can be appreciated if one considers the interior volume can be as large as 226,534 m^3 (8 million ft^3). This volume of air has a mass of about 283,495 kg (625,000 lb), or about the same mass as that of 1.5 diesel train locomotives. Moving that much mass requires a significant amount of acoustical energy.

Acoustical Treatment

Acoustical treatment for domed stadiums faces the same challenges of appearance, abuse resistance, space requirements, and cost as it would for any other building. However, there are two very significant differences with domed stadiums, the most important being the area to be treated. The stadium roof can be nearly 2.3 hectares (7 acres), and so the cost of treating the entire roof can be substantial. This is further complicated by the current architectural design trend of trying to introduce as much natural light as possible into the seating bowl, leading back to translucent ETFE being used for the roof because it is more architecturally flexible, lighter, and less expensive than traditional glass systems. The glass systems are still used for vertical surfaces, especially operable walls, at the end of domed stadiums that can open and close as seen at Allegiant (**Figure 2B**; see bit.ly/AT-GS1), Lucas Oil (see bit.ly/AT-GS2), and AT&T (see bit.ly/AT-GS3) stadiums.

The net result is that when the project budget allows, nontranslucent surfaces are treated with conventional sound-absorbent materials, such as wall panels and suspended baffles. Stadiums in St. Louis, Missouri, and Toronto, Ontario, Canada, have extensive roof sound-absorbent treatments, made possible by their solid, metal deck roof systems. St. Louis uses a suspended baffle approach (**Figure 2C**), whereas Toronto features applied fiberglass board to avoid wind issues with its operable roof.

How are these acoustical challenges addressed? For sporting events, with a premium for natural light and an emphasis on speech intelligibility from the house sound system, fixed sound-absorbent treatments and careful sound system design, setup, and operation are required. The key for a successful sound system design is controlling the directivity of the loudspeakers and speaker arrays to minimize sound hitting nonseating areas and to limit the overlap from other loudspeaker zones that can create delayed arrivals impacting intelligibility. The threshold design and system setup goal is to achieve Speech Transmission Index of Public Address systems (STIPA). STIPA values can fall between 0 (no intelligibility) and 1 (perfectly intelligible). Thousands of STIPA measurements in dozens of sports facilities have indicated that there are minimal speech intelligibility complaints from spectators when a 0.55 STIPA value is achieved.

In contrast, for concerts, natural light is not expected and can interfere with viewing the LED video displays and theatrical lighting, along with the fact that most such events occur in the evening. Use of the building for both sporting events and concerts provides the opportunity to provide temporary acoustical treatments, most commonly synthetic velour drapery for vertical surfaces such as glass end walls and, in rare cases such as the Houston Livestock Show and Rodeo concert series, over the translucent portions of the roof. There has been some investigation of permanent and variable acoustical systems for domed stadium roofs. However, none of these concepts have yet survived the budget pressures of the projects.

Good sound quality and speech intelligibility can be difficult to achieve in domed stadiums. Even when optimized, differences in speech clarity and musical quality may be experienced across the seating sections. This is especially true for concerts, where the best sound quality occurs at seats where the direct sound from the loudspeakers has very high direct levels compared with multiple arrivals from reflections and other loudspeakers. Seating where the reflected and reverberant sound levels are closer to or exceed the level of the direct sound are at a disadvantage.

Large Arena Venues

Arenas typically have seat counts of between 5,000 and 25,000 people that is often similar in seating capacity to amphitheaters. However, these venues often have smaller seating capacities than stadiums. The main arena bowl is usually a fully enclosed, large-volume space presenting unique acoustic challenges. The stadiums and outdoor performance venues previously discussed are partially or wholly in the open air that allows some dissipation of the high sound levels so there is not as much concern about room acoustic design and finishes as in arenas. Although there are similarities in the different types of large venues in terms of bringing large numbers of people together to listen to and participate in group events, the acoustical challenges in arenas are perhaps more critical and focused than in traditional acoustical concerns, more so than in the other large venues.

The multiuse arena form emerged in the United States during the 1960s and was originally used for both basketball and ice hockey. A visual focus was created on the player or performance surface, usually the lowest point in the arena, with seats arranged 360° around it. Stepped seating allowed sight lines for audience members, providing a full view of that surface. The view of the players/performers or scoreboards/other visual media often took priority, and little attention was given to acoustics.

By the end of the 1960s, however, arenas were often the location of choice for live pop music acts to play as concerts became more prevalent. Acoustics in these venues were a challenge from the outset due to the large volume of the spaces and insufficient sound-absorbing treatments. Large, stacked loudspeaker systems were often located on an end stage to push out high sound levels that often struggled to provide coverage over large parts of the audience. The speaker stacks also resulted in "echoes" of speech and music when sounds propagated out from the speakers and reflected back to the stage or front seats as "slap back" echoes, with long delays in arrival compared with the direct sound.

Over time, the arena form developed to accommodate more event types, with these shaping the surface or stage into a way that could improve the acoustics. The most common developments were the rectilinear box with seats around the perimeter; horseshoe bowl; full bowl with seats in an oval shape surrounding the playing field; and large fan where the side walls angle out from the stage. In suburban locations, where noise emission was not an issue, lightweight, parabolic, concave roofs were inexpensive and efficient to build. The negative issues of the larger interior volumes and poor sound isolation were not considered a major concern given the limited options for where events could be hosted.

Three sound system forms dominated in these types of arenas: the central cluster, distributed clusters, and fully distributed systems. The advantage of the latter two forms was typically smaller groups of loudspeakers that did not interrupt sight lines, with the ability to receive a feed from the mix of a live event and supplement touring sound systems to provide coverage in the hard-to-reach areas farthest from the stage. This saw the central cluster almost entirely phased out by the early 1980s.

Acoustic design was considered a priority during the mid-1990s, when a confluence of issues resulted in a shift of emphasis.

- Demand for live music began to increase, and large venues returned to urban centers, often as regeneration projects. Multiple large venues began to compete for events.
- A statutory requirement demanded that places of public assembly have public address/voice alarm (PAVA) systems capable of intelligible speech in emergency situations.
- Advances in sound system technology resulted in house and touring systems capable of much higher sound levels, at significantly improved quality, particularly at low (bass) frequencies, This has resulted in the need for the careful design of interior room acoustics, including both provision of appropriate acoustic finishes and minimizing the reverberant interior volume of the space.

High concert sound levels and location of venues in urban areas require higher sound-insulating building envelopes to achieve stringent noise limits at surrounding residences. This requires a clear understanding of nearby noise-sensitive receptors such as dwellings and hospitals at the outset of a project so that an adequate sound-insulating performance can be achieved. This typically has a significant impact on the architectural and structural design of the building, especially the roof. Getting it wrong is usually extremely costly or impossible to rectify once the arena is opened unless a conscious decision is made to be able to easily add components to the primary constructions later.

Today, the acoustic experience of the arena interior and its impact on the environs is considered the paramount design concern for a successful facility. Consequently, fundamental design decisions, including the site and orientation, bowl form, height, roof shape, roof geometry, and interior finishes, require acoustical input from the earliest stages of a project.

Acoustic Features

The resulting size and shape of the arena cannot always provide a natural room acoustic response consisting of a strong direct sound, early sound reflections from overhead and the sides, and diffuse reverberation for the audience and supportive reflections for the performers to be able to hear each other while playing because the room surfaces are long distances away from the listeners. Instead, sound quality is facilitated by audio systems that must provide a uniform loudness and frequency response of direct and reflected sounds over the entire audience area; maintain directional cues to the location of the sound sources; and have arrival times of sounds from direct and fill loudspeakers that reinforce the sense of sounds coming from the stage while surrounding or immersing the audience in a spatial audio-listening experience.

All of this means that the room acoustic design must support and complement the sounds propagated from the loudspeakers. For example, controlling sound reflections from natural acoustic and amplified sources to avoid long delay times and confusing directional cues is critical to a successful acoustic outcome. Moreover, room volume must be minimized as much as practical to reduce excessive reverberance, and the height and length of the arena should only be what is required to get the audience as close as possible to the performers and for audio, visual, lighting, and theatrical equipment to function.

Arena room volumes are inherently large, with the height driven by the need to achieve optimal sight lines along with a safe riser height for the successive rows of seating. The geometry of the roof is a major factor in this regard. Close collaboration among architect, structural engineer, and acoustic consultant is required to optimally resolve these often competing design challenges. Preference should be given to flat or convex roof forms as viewed from the interior. Concave or parabolic forms that increase the room height and volume and focus the sound should be avoided. Floor area that extends significantly beyond the last row of seating should also be avoided.

It is usually necessary to introduce significant areas of broadband and low-frequency sound-absorbing and sometimes diffusing treatments on walls, soffits, and the underside of the structural external envelope to reduce strong reflections from the sound system striking these surfaces because the reflections can negatively impact speech intelligibility and music clarity. Vertical and horizontal glass surfaces usually need to be angled to reflect sound energy directly to a sound-absorbing surface to avoid creating echoes. Sound-absorbing finishes should be effective across the audible frequency range, with increasing attention required for low-frequency sound control. This usually requires the acoustical design of a special ceiling system that includes relatively thick sound-absorbent material suspended about 2 m below the roof, with sufficient gaps to get a maximum sound-absorbing performance from both the front and rear sides of the material as well as additional low-frequency panel absorption from the suspension of the material. The need for these materials in fully enclosed arenas is perhaps greater than in open air or partially enclosed amphitheaters and stadiums because the absorption of the low-frequency sounds by the panels is the only way they can be reduced. There are no large openings for the long-wavelength, low-frequency sounds to escape from the venue. Finally, the floors usually need to incorporate some impact sound control but generally do not include any carpet due to maintenance issues.

Sound-absorbing seats are used throughout the bowl to minimize acoustic differences between the unoccupied and occupied conditions especially during setup, testing, and sound check prior to events when an audience is not present in the room. Some spaces may require variable acoustics to accommodate different performance types. This can be especially true in rooms where the roof is be opened. The incorporation of audio and visual technology systems, control rooms, and similar spaces that connect to the main performance space all need to be considered. When used as elements in an integrated holistic approach to the architectural and acoustical design of the arena, these concepts should result in a sufficiently controlled room that supports the sound system and reaches criterion levels for acoustical quality.

Case Study: Barclays Center

The Barclays Center arena in Brooklyn, New York, required acoustical renovations when its original lightweight roof resulted in a lower than ideal inside-to-outside sound reduction, resulting in noise impacts to surrounding residences. The structural capacity of the roof would not accommodate significant weight being added to the existing building. Thus, rather than add weight, off-site sound emissions were reduced by installing a green roof

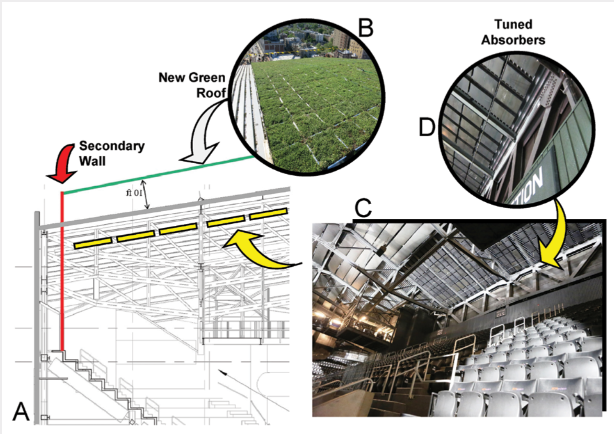

Figure 3. ***A:*** *concept section drawing of the Barclays Center in Brooklyn, New York.* ***Green line:*** *new green roof above the original roof.* ***B:*** *photograph of the new green roof installed as a second roof layer above the existing roof to reduce off-site sound transmission.* ***C:*** *interior photograph showing tuned resonant-absorbing panels above the seating area.* ***D:*** *enlarged photograph of the absorbing panel, with a metal facing and absorbent fill suspended below the main roof of the building.*

system of modular, prefabricated sedum trays that form the base for the green roof to allow vegetation to grow, hold water and nutrients, and root above a structural roof deck (see **Figure 3**; also see bit.ly/AT-GS5).The trays are inherently damp due to the properties of the sedum, located 10 ft above the original roof. The green roof, combined with the airspace between it and the original roof, provided improved sound isolation while meeting the original masterplan concept for a green roof.

Inside the room, the parabolic roof form, initially chosen for structural efficiency and weight, resulted in a larger than ideal acoustic volume. This led to complaints about the clarity and quality of sound throughout the arena, especially on the event floor, upper seating bowl, and seats furthest from the stage when the room was used for musical events.

To solve these problems, the interior acoustics were upgraded by the addition of metal sound-absorbing panels over an enclosed airspace, tuned to absorb 50- to 100-Hz energy placed across the entire upper audience seating area, helping to reduce the overall sound pressure level. The house sound system was also optimized to accommodate individual time delays to the upper bowl loudspeakers, allowing them to be individually time aligned with sound from the stage system, providing a significantly improved audience experience. The design concepts for the renovation of the space are illustrated in **Figure 3**.

The Outlook for The Future

Technology continues to be used in creative ways as part of sports, concerts, and other large-scale entertainment events as a mechanism to transform a relatively passive engagement into an active, immersive experience for performers and audience. Therefore, large arenas, stadiums, and amphitheaters around the world are likely to become more technology intensive in the future. Technology infrastructure requires careful planning and must allow for easy connection or deployment of new technology in the architecture. The design challenge is how to give the space architectural character while allowing this technological overlay to happen seamlessly. The use of technology, including emerging immersive audio and visual (VR), augmented reality (AR), and extended reality (XR), as well as development of new concert and performance formats and emerging sports (e.g., eSports) will have a continuing impact on the future development of the typology and the acoustical design issues involved.

Large-scale performance spaces, whether inside or outside, pose inherent design challenges given the number of spectators they entertain and the difficulty in containing sounds of heavily amplified performances. Many people go to these spaces to share a collective experience with a group of people, to have community, enjoy the event, and leave energized by the whole experience. However, there are also many who are unwilling participants in the performances, who experience the by-product of the event without immersion in the event. An on-going dialog between the performance venue and its nearby inhabitants via personal communication and technological systems is needed so that multiple viewpoints are considered.

As technology moves ahead, perhaps new and creative ways to further improve the acoustic environment of large-scale performance venues internationally will develop that may help to further optimize the participants' experience and reduce the impact to the surrounding community. The use of meta-materials, active phase cancellation of sounds with loudspeakers, and other interventions are on the horizon to provide the performances of the future with even better, more controlled sound fields and more optimized acoustic environments. Research challenges for effective lightweight materials that can absorb low-frequency sound and reduce emissions from facilities to surrounding areas, to spatial audio and visual systems for large venues, and to hearing health concerns for recreational noise exposure are issues requiring future development.

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Conversation with a Colleague: Karl Grosh

Karl Grosh
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Karl Grosh

Karl Grosh is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague." He is a professor of mechanical engineering and biomedical engineering as well a member of the Kresge Hearing Research Institute, University of Michigan, Ann Arbor. He received his BS and MS degrees in engineering science from The Pennsylvania State University, State College, and his PhD in mechanical engineering from Stanford University, Stanford, California. From 1987 to 1990, he was a research scientist at the Naval Research Laboratory, Washington, DC. He is a Fellow of the American Society of Mechanical Engineering (ASME) and the Acoustical Society of America, and in 2019, he received the ASME Per Brüel Gold Medal for Noise Control and Acoustics. From 2007 to 2009 and 2017 to 2019, Karl acted as associate chair of mechanical engineering; his current service activities emphasize diversity, equity, and inclusion in engineering. He cofounded a piezoelectric microelectromechanical system (piezoMEMS) transducer company, Vesper Technologies. We asked Karl to give us his elevator pitch and then to elaborate on his inspirations, contributions, and hopes for the future.

Give your "elevator speech" about the thrust(s) of your scholarly work over your career.

A major focus of my work has been in the study of biological and engineered acoustic transduction. My work seeks to understand the fundamental structure-function relationships in the mammalian cochlea by building mechanistic mathematical models. We test hypotheses of active processes by comparing with and predicting experimental outcomes obtained by my amazing colleagues in cochlear electrophysiology. By understanding the cochlea well enough to model it, we hope to aid in the protection of hearing and in the development of noninvasive testing procedures, auditory prostheses, and sound-processing algorithms.

I started work in engineered electroacoustic transducers in 1985 during my master's thesis work at the Penn State Applied Research Lab's sonar research lab by designing and assembling piezoelectric actuators and sensors for a wave number-frequency measurement system. Fast-forward to the University of Michigan where we now leverage the tremendous dimensional control available by using microelectromechanical systems (MEMS) techniques to build miniature acoustic and vibrational sensors, first for consumer electronics and, more recently, for middle ear accelerometers for use in completely implantable auditory prostheses. Finally, our group has also been exploring the design of acoustic metamaterials using active, subwavelength electromechanical designs to achieve sound-quieting and nonreciprocal wave propagation. I thought I was a latecomer to the relatively new field of metamaterials; I recently realized I had been studying one of the world's oldest active acoustic metamaterial systems, the mammalian cochlea!

What inspired you to work in this area of scholarship?

Luck and amazing people! In the fall of 1983 while an undergraduate at Penn State, my advisor Sabih Hayek (2003 Trent-Crede Medal awardee and Professor Emeritus of Engineering Science) called to offer me a job to study the diffraction of sound by highway noise barriers. I remember fondly telling Sabih that I'd have to ask my parents first (they were delighted!). This position opened me up to the world of acoustics, including the beautiful geometric theory of diffraction, advanced mathematics,

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and the joy and frustration of comparing theory to experiment. Moreover, I was immersed in this world of research, where people were actually paid to do this fascinating work and learn new things. I was hooked.

I have been lucky to have supportive mentors throughout my career: Sabih, Jack Hughes, and Courtney Burroughs at Penn State, Earl Williams at the Naval Research Lab, and Peter Pinsky at Stanford (see profiles.stanford.edu/peter-pinsky). They always strongly challenged me during meetings and strongly supported me with advice and resources to achieve my goals. By far my best and strongest partner has and continues to be my wife Linda, whose support lets me focus when the page before me is empty and keeps me strong when times are the toughest. She was the first to realize that I really needed to obtain a PhD to attain my goals and has supported and encouraged me at each step of the way in my career.

Of all your contributions during your career, which are you most proud of and why?

When I was recruiting Bobby Littrell to my lab as a PhD student in mechanical engineering at the University of Michigan, he mentioned that he was very interested in research in acoustic transducers (microphones and loudspeakers in particular). I told him in no uncertain terms that I thought that microphone and loudspeaker research was not a fertile area, but I did have the great idea to build an active, engineered cochlea; he took that challenge. We worked toward that goal but quickly realized that integrating microscale piezoelectric bimorphs to act as sensing and amplifying outer hair cells (OHCs) in our microfluidic biomimetic cochlea was too big a challenge for a reasonable-length PhD project. So we pivoted to perfecting the design and manufacture of these tiny biomorphs first. Bobby convinced me to work on a microphone design as the model problem using the biomorphs (to provide some purpose to the design before returning to the biomimetic cochlea). For any number of reasons, I was sure this design would not be successful, but Bobby quickly disavowed me of this notion by inventing a better mousetrap, building a low-noise piezo-MEMS microphone for the first time. This became Bobby's thesis topic. I was never so glad to be so very wrong!

We went on to cofound a company that had over 50 employees worldwide and that was funded by Small Business Innovation Research (SBIR) grants, venture capital, and sales revenue. Our company, Vesper Technologies (see vespermems.com), was eventually acquired by Qualcomm. It is gratifying to have an outcome of academic research result in a practical device and even more so to see it successfully commercialized thanks to the hard work of many talented people. This project, our piezo-MEMS microphone, is a nice example of how research works, not always in the way originally intended, but it works. Sometimes we are fabulously successful. Often, we fail, but even when research fails, it succeeds because we teach others that a certain pathway is unproductive and an alternative should be sought. My philosophy is to let talented people follow their passion and seek to provide resources to make that happen.

The cochlear biomimicry research led to our interest in ultraminiature sensors. Now our transducer research has circled back to the cochlea, and we seeking to use these sensors as part of a totally implantable auditory prosthesis.

What are some of the other areas in which you feel you made substantive contributions over your career?

Since the discovery of OHC somatic electromotility in 1985 by Bill Brownell and colleagues (see bit.ly/AT-Bownell), a question that dogged cochlear biophysics was whether OHCs could overcome the filtering associated with the membrane's basolateral capacitance and conductance. Using mathematical models for the active and nonlinear response of the cochlea to acoustic input, we have demonstrated that OHC somatic motility is able to power the biologically vulnerable process known as cochlear amplification. There are still open scientific questions plaguing cochlear mechanics, for instance, the role of nonlinearity in processing complex sounds like speech, is still incompletely understood. To aid in developing mechanistic explanations for experimental results as well as to conceive of new theories, we have sought to develop a cochlear model that can be both challenged by new biophysical experimental data and enriched by the same data (to improve the model). In that way, it provides a platform for a mechanistic understanding of cochlear processing.

Another line of work that I was involved with and am proud of was focused on both theory and experiment for growth and remodeling of tendons and ligaments. This research focused not only on these tissues in their natural setting but also in a bioreactor setting as part of an effort to learn how to grow replacement tissues. Working with a team of researchers, including my mechanical engineering colleagues Ellen Arruda and Krishna Garikipati at the University of Michigan, we developed procedures for tissue engineering of tendons and ligaments using cells from the host as well as characterization of the constructs' mechanical behavior and phenotype. Furthermore, we developed a nonlinear model for growth and remodeling of biological tissues that is widely cited.

What do you think are the most pressing open questions that you would like to focus on over the next 5-10 years?

Hearing aids and cochlear implants represent amazing technology. I would like to see totally implantable hearing aids and cochlear implants become a reality, to improve the activities that auditory prostheses users can partake in, allow 24/7 use, and allow for a more naturalistic sound input (using the natural design of the pinna and ear canal). In this way, we may remove a barrier for adoption and allow for more patients to utilize these devices.

The nature of the cochlear amplifier is still in debate nearly 40 years after the discovery of the electromotility of OHCs by Bill Brownell. The structure of prestin and the components of the mechanoelectrotransducer (MET) channels are now tantalizingly close to being completely described at the molecular level. With these data in hand, I hope that we as a field can come to a complete structure-function relationship for OHC-mediated active processes.

Finally, both cochlear-inspired and engineered nonlocal active acoustic metamaterials hold the promise of unprecedented control of wave propagation in acoustic media (structures and fluids). I would like to see these materials studied in more detail because they hold great practical promise and scientific interest.

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Promoting Global Acoustical Collaboration

Andy W. L. Chung and Adrian KC Lee

Introduction

The International Liaison Committee (ILC) of the Acoustical Society of America (ASA) underscores the importance of global interaction and cooperation in the expansive realm of acoustics. The Excellence in Acoustics Around the World session (held virtually in June 2021 at the 180th ASA meeting; see bit.ly/3QWDg3y, pp. A47-A49) was a testament to this commitment, serving as a vibrant forum for acousticians from across the globe to connect and share their expertise.

Charting Acoustical Horizons: A Global Perspective

Led by Brigitte Schulte-Fortkamp, chair of the ILC and founding advisor of the East and South East Asia Regional Chapter of the ASA (ESEA), and Andy Chung, representative from the ESEA, this session hosted experts from Asia, Europe, and the United States. Featuring nine invited papers, the participants presented and engaged in discussions on the most recent developments and collaborative initiatives in acoustic research and education. Four themes emerged from this globally minded session (Chung and Schulte-Fortkamp, 2021).

Here we highlight the themes in acoustics research, education, and the sharing of expertise on a global scale. We also take a deep dive into the acoustical advancements across the Asia-Pacific (APAC) landscape to spotlight the technological vanguards of that region.

Crossing Traditional Boundaries in Arts, Engineering, and Earth Sciences

The transformative power of acoustics extends well into architecture, urban development, and environmental preservation. Its role is not only evolving but is also revolutionizing these fields, becoming a vital component in their planning and execution strategies.

The Power of Partnership

Embracing international synergies aligns with broadening markets and fostering mutual growth. Synchronizing our initiatives with comprehensive goals, like those set by the United Nation's sustainable development objectives (see tinyurl.com/4hamwbh4), transcends mere expansion of influence. It creates a domino effect of beneficial outcomes, spreading through diverse industries and crossing national boundaries.

Charting Excellence with "EXCEL"

In the spirit of international cooperation, a universally adaptable guideline becomes invaluable. The "EXCEL" framework is crafted with this in mind, aiming to advance global acoustical excellence. It is built on five foundational pillars:

E, Empowering knowledge transfer;
X, eXtending application of acoustics to other sectors;
C, Capacity building;
E, Engaging stakeholders; and
L, Long-term strategic management toward healthy and harmonized cities and societies.

This framework is not just a guideline but a globally adaptable model that ensures we remain harmonized, setting standards that have a universal resonance and facilitate robust, impactful international collaborations.

Digital Pioneering

The digital outreach of the ASA's international chapters is carving out a new frontier, spotlighting an enthusiastic digital community ready to connect and evolve. Members of the ILC hosted virtual events during the pandemic, with the hope of linking up with acousticians in the APAC region. With over 430 active participants from a registration pool of 700 engaged in these events, this high level of engagement indicates a rich untapped potential in online education, virtual collaboration, and digital commerce within the acoustics industry.

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Acoustical Advancements Across the Asia-Pacific Region

The APAC region exemplifies a harmonious blend of heritage and progress in the field of acoustics. Here we present key highlights, emphasizing the diverse acoustical approaches across the Asia-Pacific region. Drawing from insights shared by the speakers in the aforementioned session Excellence in Acoustics Around the World, we present the following highlights.

Soundscapes and Perception

At Tokyo Denki University, Tokyo, Japan, Akita (2021) delves into soundscapes, concentrating on their perception and the complex web of factors that shape this experience (see www.a.dendai.ac.jp). Anchoring his work in the International Organization for Standardization (ISO) 12913-1:2014 standard (Schulte-Fortkamp, 2019), Akita (2021) highlights a gap in Japan's research on soundscape perception and cognition. He brings attention to the profound influence of individual backgrounds, values, and even visual stimuli on the perception of soundscapes, suggesting a layered understanding of the concept. To cultivate enriching soundscapes, Akita advocates for more in-depth research. His goal is to design acoustic environments that are not only audibly pleasing but are also reflective of the cultural and personal nuances of the audience.

A Symphony of Tradition and Innovation

India's acoustical narrative is characterized by a deep-seated cultural heritage enriched by innovative technological strides. Agrawal (2021) has cast a spotlight on the country's advancements, particularly in AI-driven acoustical systems, suggesting a future where technology and traditional soundscapes intersect to transform everything from residential living to healthcare diagnostics. This is with the backdrop of integrating a nuanced production of classical music and the resonant acoustics of ancient temples with cutting-edge research and technology.

Complementing terrestrial acoustics, India's commitment to oceanic acoustic research is evident through the efforts of the National Institute of Ocean Technology, Chennai, India, and the Indian Institute of Technology Madras, Chennai. Researchers like Potty et al. (2021) are delving into the ocean's depth, seeking to unravel its secrets while fostering international partnerships that underline the country's extensive research capabilities.

Innovating Urban Acoustic Solutions

Singapore's metropolitan heartbeat brings with it the challenges of urban noise. Leading the charge for such challenges is Lee (2021) from National University of Singapore. Lee's research is a testament to the innovation required in tackling noise pollution in bustling urban environments. His exploration into sonic crystals, acoustic metamaterials, and noise barriers showcases cutting-edge solutions that can redefine urban acoustic landscapes.

One of Lee's standout proposals is the integration of features like Helmholtz's resonators and microperforated structures into sonic crystals. Such innovations promise optimal noise reduction, a boon for densely populated areas. Ventilated acoustic metastructures, combined with Helmholtz's resonators, further enhance this noise reduction capability, highlighting Singapore's commitment to acoustic comfort. He also advocates allowing smartphones to double as precise sound level meters, making environmental noise measurements more accessible to the masses.

A Beacon of Acoustic Excellence in the Asia-Pacific Region

Taiwan demonstrates a profound commitment to acoustic excellence, as outlined by Juan and Tsaih (2021). The nation boasts comprehensive acoustic regulations and standards, pioneering particularly in addressing low-frequency noise with regulations for the 20- to 200-Hz range. This foresight in sound management reflects Taiwan's holistic approach and alignment with international benchmarks. The local Taiwan Acoustical Association (established in 1987) also plays a pivotal role in uniting sound professionals and enthusiasts.

Taiwan's academic institutions, including at least 14 top universities offering specialized acoustics programs, contribute to its acoustical innovation. The National Taiwan University of Science and Technology, Taipei, has been particularly influential, with its architectural acoustics program involved in high-profile projects like the Taichung Metropolitan Opera House, Taichung, Taiwan, and the Taipei Pop Music Center, Taipei, Taiwan. With around 187 acoustic-related patents since 2004, Taiwan's academic and practical contributions to the field are both substantial and impactful.

From Melodies to Modern Sound Practices

The Philippines, with its rich cultural and colonial history, holds a unique position in the acoustical world. Hermano and Galan (2021) offered insights into the Philippines' acoustic environment, capturing its essence from historical, cultural, and modern perspectives. They highlighted the nation's musical prowess, which has given rise to world-class talents. Yet, the gap in sound education has led to misconceptions about sound and its health implications. The duo emphasized the pressing need for sound education, advocacy for sound measurement tools, and the formulation of legislation promoting sound practices. By addressing these gaps, the Philippines can harness its innate musical talents while ensuring sound health and well-being for its citizens.

Navigating the Urban Acoustic Landscape

In Hong Kong, a city characterized by its dense population and ceaseless activity, acoustical challenges are a central concern. Yeung from Hong Kong Institute of Acoustics (2021) showcased the city's innovative strides in managing environmental noise, notably through the creation of the world's first three-dimensional traffic noise mapping. This tool not only locates noise pollution but also provides valuable data for those shaping the city's future. The city's commitment to understanding how urban noise affects residents' health and quality of life is further underscored by their extensive noise-health survey, with inputs from over 10,000 households.

Advancements in indoor and architectural acoustics are also at the forefront, driven by the development of luxury hotels and sophisticated performance centers as Hong Kong evolves into an international financial hub. The demand for acoustic excellence has fostered local and international collaborations, leading to remarkable developments such as the largest theater for traditional Chinese opera and innovative residential designs featuring open-type windows for noise reduction.

Collaboration in Acoustics Research and Education

Zhang, University of Mississippi, Oxford, and Wang, Chinese Academy of Sciences, Beijing, (2021) discuss the current state of acoustics research and education in China, emphasizing mutual interests in collaboration with American acoustical societies. The talk highlights joint efforts like conferences, funding for scholars, and exchange publications, with examples like the *Journal of Applied Acoustics* and the *Chinese Journal of Acoustics* featuring bilingual greetings from the ASA Editor in Chief (Lynch, 2019). The speakers address challenges in initiating collaborations and emphasize the importance of ongoing international communication and cooperation for future advancements in the field.

Current and Future Challenges

The role within the ASA ILC is not only to bear witness to the acoustic innovation in the APAC region, but it also serves as a venue for our members to actively engage, contribute and shape the narrative of acoustic excellence. This region is emerging as a hub of acoustical innovation, filled with both potentials and obstacles. Delving into these challenges helps us understand what we must overcome to progress:

Language Barriers

The linguistic mosaic of the APAC region enriches its culture but can complicate communication. Differences in acoustical terminology and subjective perception can disrupt the exchange of knowledge and understanding.

Cultural Variations

Acoustics is intrinsically tied to our environments and thus our cultures. It is shaped by diverse traditions, as seen in India's music and Hong Kong's urban planning. Recognizing and respecting these cultural nuances is key to successful collaboration.

Logistical Challenges

The dichotomy between urban and rural areas in the APAC region presents unique obstacles and opportunities. Projects like three-dimensional (3D) noise mapping and AI-driven systems highlight the contrasts between densely populated cities and expansive rural areas. Infrastructure limitations, regulatory diversity, and supply chain issues pose additional difficulties. But with adaptive strategies and cooperation, we can strive for acoustical excellence across the region.

Trust Building

In fostering international collaborations, trust is crucial. It goes beyond technical partnerships to mutual respect, understanding, and shared objectives.

Technological Adaptation

Keeping pace with rapid technological changes is a formidable challenge. Ensuring that these technologies are accessible and beneficial across the region is essential.

Despite these hurdles, we are committed to harmonizing the future of acoustics in the APAC region and beyond by cultivating trust, understanding, and sharing our expertise.

Summary and Way Forward

The insights presented in this essay are derived from a specific session, representing only a glimpse into the acoustics landscape of the Asia-Pacific region, with a specific focus in the areas of arts, engineering, and earth sciences. Moving forward, we plan to engage with other regions for a more comprehensive understanding as well as extending to areas in the life sciences (e.g., communications sciences where the diversity of languages play an especially important role). Nonetheless, these recent discussions underscored the importance of international education and research collaboration for the ASA and the broader community. The Excellence in Acoustics Around the World session served as a pivotal platform for acoustic experts worldwide to share insights and collaborate on research and education. The collective momentum is clear: there is a push for enhanced international collaboration and communication to further the field of acoustics, benefiting both the ASA and the larger community.

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Tuning into Change: Students Fostering Inclusion in the Acoustics Field

Marissa L. Garcia

Introduction

Students and recent graduates who are members of the Acoustical Society of America (ASA) are already serving as exemplary leaders in the acoustics field, in both research and their communities. Many, in fact, have been the driving force behind movements to foster a greater culture of inclusion in acoustics. Centering our professional spaces around inclusivity is essential for our success as a field, but sometimes it can be tricky knowing just how to spur change in one's own working environment. Perhaps the best resource we have through the ASA is learning from each other, and so, this essay highlights students and recent graduates who have, in service of the same goal, pursued many different avenues of action: research, representation, community, and even the ASA itself. The Student Council hopes that these stories spark ideas about what others can do to cultivate a greater sense of belonging at their institutions.

Power Through Research

Abhijit Roy (AbhijitRoy2025@u.northwestern.edu) is in his fourth year of his PhD program in communication sciences and disorders at Northwestern University, Evanston, Illinois. His academic journey began as a law student in India, but his passions inspired him to switch to a Bachelor of Fine Arts degree in sound design and music production from the Savannah College of Art and Design, Savannah, Georgia. After working closely with film, music, and sound effects, Abhijit became increasingly captivated by the impact that sound bears on the senses. He went on to gain a thorough understanding of sound as a physical concept through his MA in acoustical studies at Johns Hopkins University, Baltimore, Maryland. Since then, he has been pursuing a PhD at the Hearing Aid Laboratory (see bit.ly/3t1lqEF) under the mentorship of Pamela Souza (see bit.ly/3RbGDDT), where his unique background in music production, acoustics, signal processing, and hearing loss has manifested into research on optimizing the hearing aid experience for people hailing from multiple walks of life. His passion for equity and inclusion lives within his actual research design, the impacts of which could improve hearing aid performance no matter the preferred language and could also motivate lower hearing aid costs overall.

> "Motivations for the early portion of my PhD research were primarily focused on understanding whether language specificity in hearing aid signal processing may result in better outcomes. We compared the performance of English- and Mandarin-speaking individuals on their phoneme perception in various frequency compression settings. Our results found that there are some detailed variances in perception that could have a possible impact on clinical tools used to optimize frequency compression. In addition to assessing language-specific signal processing, I am also interested in creating more efficient compression and filterbank designs that can lower the overall cost of hearing aids. I am exploring various acoustic metrics and solutions to inform novel hearing aid signal-processing regimens, which can reduce computational requirements."

Power Through Representation

Olivia Heui Young Park (hkp5188@psu.edu; see bit.ly/41feOz2) will graduate in Summer 2025 with a PhD in acoustics from the Pennsylvania State University, State College. Hailing from Seoul, Korea, she earned her BE and MEng in mechanical engineering from the Cooper Union for the Advancement of Science and Art, New York, New York. Since then, she has set her sights

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on better understanding the human aspect of acoustics through her research at the Sound Perception and Room Acoustics Laboratory (SPRAL; see bit.ly/41hYyxq) under the guidance of Michelle Vigeant-Haas (see bit.ly/4ae1miX). Here, she investigates the effects of noise on human cognition, physiology, perception, and speech intelligibility and applies these insights toward implementing realistic room acoustic environments. She also serves as the architectural acoustics representative on the Student Council. Through outreach materials and events, she has wielded the tool of representation to actively improve diversity in her academic environments.

> "Representation and spreading awareness are some of the best ways of fostering inclusive, diverse environments. When I served as the secretary and then vice president for the Penn State Chapter of the ASA, I tried to incorporate different methods of promoting such environments. As secretary, I created monthly newsletters featuring events that happened during each month and took advantage of March being Women's History Month to promote female students, faculty, and staff. I featured 'in-action' photos of the department's female members conducting research or outreach. I also participated in various recruiting and outreach events to help promote diversity and inclusion. As an international student and a female person of color, I know how crucial representation is, especially to younger, underrepresented students. I love participating in outreach events because I get to teach younger students acoustics-related concepts through demos and lectures. I led the acoustics portion of the AEspiring Architectural Engineering summer camp (see bit.ly/48bGYxk) last year and have participated in the programs Ask a Scientist, ENVISION, Young Women in Science, and more. It is so rewarding to see students gain confidence and interest in acoustics and to hear from students who are underrepresented, like me, say that they feel validated seeing me as an instructor or even knowing that I am pursuing a PhD in engineering."

Power Through Community

Natalie Kukshtel (nkukshtel@whoi.edu; see bit.ly/47OKmOK) is in her fourth year of her PhD program in mechanical engineering and applied ocean physics in the Massachusetts Institute of Technology (MIT)-Woods Hole Oceanographic Institution (WHOI) Joint Program in Oceanography/Applied Ocean Science and Engineering (MIT-WHOI JP) located in both Cambridge, Massachusetts, and Woods Hole, Massachusetts. After receiving her BS from Northeastern University, Boston, Massachusetts, she gained experience working for two years as a mechanical engineer in defense robotics. Now representing underwater acoustics on the Student Council, she researches the use of autonomous underwater vehicles and computational ocean acoustic modeling to better understand underwater acoustic propagation along the New England Shelf Break. To level the playing field in acoustics, she has concentrated her efforts on a key part of the pipeline, helping acoustics-curious graduate students decipher the hidden curriculum behind applying to graduate school. She has served for three years as a board member on the MIT-WHOI JP Applicant Support & Knowledgebase (JP ASK) program, which aims to do exactly that.

> "The MIT-WHOI JP ASK program is a mentorship program established in 2019 by graduate students who wanted to lower the barrier for the graduate school application process, particularly for potential students who are underrepresented and/or unfamiliar with ocean sciences and engineering (including ocean acoustics!). We advise and support prospective students through the graduate application process, with a focus on increasing the diversity of incoming students in these fields. JP ASK is run by a board of graduate student volunteers, and we pair prospective applicant mentees with current graduate student mentors. Through these one-on-one interactions, mentees get personalized advice for their applications as well as a realistic look into the life of a graduate student. Although the program advises mentees across various ocean science and engineering disciplines, we believe it's important to spread awareness of the ocean acoustics field due to the limited representation it has in most undergraduate studies. Since starting JP ASK, we've matched nearly 600 mentees from around the world, whose demographics are more diverse than our graduate program and ocean sciences overall."

EeShan Bhatt (Eeshan.Bhatt@appliedoceansciences.com; see bit.ly/488Tg9z) earned his PhD in mechanical and oceanographic engineering at the MIT-WHOI JP located in both Cambridge and Woods Hole. Although he is now a staff scientist at Applied Ocean

Sciences based in Springfield, Virginia, his dissertation research involved developing real-time ray identification to aid underwater navigation in the Beaufort Sea under the supervision of Henrik Schmidt (see bit.ly/41haak6). On graduation, EeShan received the George P. Panteleyev Award in honor of his commitment to improving graduate student life. One facet of this mission included being among the founding members of the MIT-WHOI JP ASK Program that Natalie now oversees. While he has since passed the baton to the new leaders of the program, he is reflective on the influence of starting the first ocean science applicant assistance program.

> "I always felt that I lucked into studying ocean acoustics. Through many heartfelt conversations with peers in my first few years of graduate school, we realized that the most common and visible pathways to a graduate degree in oceanography (and perhaps this is generally true for most STEM fields) were relatively inaccessible opportunities: having grown up or summered near the ocean, having other academics in the family, or having significant prior diving or sailing experience. I was particularly motivated to start JP ASK because it felt like an effective way for us as students to lower the barrier for others to consider joining the ocean science and engineering community. Seeing JP ASK thrive with new cohorts of student leaders and mentors has been even more rewarding than starting it. I feel confident that this kind of program, by students and for students, will continue to be the kind of wholehearted welcome to graduate school everyone could use."

Power Through the Acoustical Society of America

Elizabeth Weidner (ereedweidner@ucsd.edu; see bit.ly/4ad0evR) earned her PhD in oceanography from a joint program between the University of New Hampshire, Durham, and Stockholm University, Stockholm, Sweden. A previous Student Council member representing acoustical oceanography, Elizabeth is now a postdoctoral fellow at Scripps Institution of Oceanography, La Jolla, California, and an affiliate research professor with the Center for Coastal and Ocean Mapping, Durham, New Hampshire. Her research encompasses the broadband acoustic characterization of high-latitude glacial fjords, gas bubbles, ocean water column structure, and buoyant fluid emissions. Her experiences in the ocean acoustics field led her to set her sights toward strengthening inclusion via the ASA itself.

> "Underwater acoustics is a male-dominated field. The lack of gender diversity is reflected in my personal experiences; sitting in a conference session, I am one of very few women. I am aware that my feelings of isolation pale in comparison to those who are black, indigenous, and people of color (BIPOC) and/or with intersectional identities. However, understanding a small piece of otherness has motivated my efforts to both educate myself and combat issues limiting diversity, equity, and inclusion (DEI) in my spheres of influence, including within the ASA. I am part of the ASA's Committee to Increase Racial Diversity and Inclusivity (CIRDI), currently chaired by Andrea P. Arguelles, originally cochaired by Tyrone Porter and Peggy Nelson. Founded as an ad hoc committee in Fall 2020, CIRDI is focused on proposing and implementing strategies to
>
> (1) Increase representation and participation of racially diverse groups in the ASA;
> (2) Build awareness of the value of DEI among the membership; and
> (3) Improve the sense of belonging of underrepresented minorities in the ASA.
>
> "The committee has pursued multiple initiatives to achieve these goals, but one that I am most excited about is the Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA). SURIEA was launched in 2021 and was specifically designed to reach underrepresented minority students, introducing them to the field of acoustics through paid research experience. During its development, one of the main focuses was building community support and participant camaraderie throughout the program to improve outcomes and retention. Since 2021, SURIEA has supported over 30 students in their acoustics research experiences, and we are in the planning phase for the next cohort right now! The application is open to students and mentors for 2024 and can be found at the SURIEA website (acousticalsociety.org/suriea)."

Conclusion

From optimizing room acoustics to making hearing aids more accessible to even modeling acoustic propagation in the ocean, these young researchers encompass a formidable range of academic expertise. Beyond making an impact in their research, however, these leaders have forged ways to support people from all walks of life whether it be through their research, representation, community, or even the ASA. The Student Council hopes that ASA members across all career stages find these stories to be empowering and emboldening, serving as the blueprint for new initiatives and sowing the seeds for the roots of change.

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