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The Acoustics of the Modern Jazz Drum Kit

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Winter 2022 Volume 18, Issue 4

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"Drum set" is a watercolor painted by Alex Tolstoy (see page 73). See more of Dr. Tolstoy's art at atolstoyart.com.

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From the Editor

Arthur N. Popper

(Re)Meet *ECHOES*[1]

I am starting my column by (re)-introducing members to *ECHOES*, a quarterly news and information publication of the Acoustical Society of America (ASA) from 1991 to 2013. I do this because as I randomly browsed the 23 years of issues, I felt like I used to when browsing the stacks in a great science library (way before the Web). I vividly recall the fun and excitement as I randomly opened journals and discovered articles and nuggets of knowledge that were either directly related to my research or perhaps that opened new areas of thinking. I had the same feeling when browsing *ECHOES* where I "discovered" material about the ASA, meeting reports, brief research reports, and many other things that I'd long forgotten or perhaps never knew. *ECHOES* is online at acousticalsociety.org/echoes.

ECHOES started in spring 1991 and continued quarterly until the end of 2013. For several years, it overlapped with *Acoustics Today* (*AT*), which first appeared in 2005. Each publication had a place. Whereas *AT* focused on longer scholarly articles, the mission of *ECHOES*, as defined by its first editor, ASA Fellow Alice Suter, was twofold: to provide brief technical articles about topics that would be interesting to and understandable by all ASA members and to provide news and current information about the ASA, including meetings and reports. (Before Dr. Suter took over as editor, she and Charles Schmid, then executive director of the ASA, served as ad hoc editors.)

In 1997, Dr. Thomas D. Rossing became *ECHOES* editor, and he continued in this role until its demise. Tom added additional material including a section called "Scanning the Journals" where he reviewed reports on acoustics from outside the pages of ASA publications. Tom passed away recently, and this issue of *AT* has an obituary honoring him (see page 85).

Rather than going on about *ECHOES*, I just encourage members to browse its pages. In particular, look at the issues in 2004 when the 75th anniversary of the ASA was celebrated. Happy discovering!

This Issue of *Acoustics Today*

Our first article, by Colleen G. Le Prell, discusses something of great relevance to many members of the ASA, loss of hearing (see articles at bit.ly/AT-Health). Colleen gives an interesting overview of what happens when someone has a hearing loss and then provides insight into some of the amazing approaches being tried that could, many years from now, offer treatment to possibly reverse hearing loss.

Our second article is by Roy Manstan. Roy is very interested in both history and sonar, and he writes about the origins of sonar in World War I. Sonar arose because of the predation on Allied vessels by German U-boats and the quest to be able to find and destroy the subs. Many well-known scientists and engineers were involved in sonar development, and Roy introduces us to many of these people. You can find other articles on this history of acoustic devices and issues at bit.ly/AT-History.

Our third article focuses on the function and form of percussion instruments, a nice addition to our overall collection of articles about musical instruments (see bit.ly/3c4ltqi). The authors, E. K. Ellington Scott (bit.ly/AT-Scott) and Andrew Morrison, discuss the physics of drums of various types and focus on the origin of the modern jazz drum kit. As part of the article, Ellington and Andrew demonstrate the instruments with several demonstration videos that are, at least in my view, totally fascinating and make the article "come alive."

In the fourth article, Dirk-Jan van Manen and Johan O. A. Robertsson provide insight into immersive wave experimentation and into approaches to providing virtual experiences to help people "hear" acoustics of spaces that have yet to be built. To help readers understand and appreciate this virtual environment, Dirk-Jan and Johan evoke ideas from *The Matrix*, and all fans of those movies will find this article a "must read."

1 *I thank Elaine Moran for sharing memories about* ECHOES.

The fifth article by Pavel Zahorik and Matthew T. Neal also discusses acoustic space but from the perspective of reflected sound. They ask the value of acoustic reflections and demonstrate how reflected sound can be a major problem in some instances, whereas it is very useful in others, such as, when controlled, in a concert hall.

I very much recommend looking at the essays in our "Sound Perspectives" (SP) section. Our first SP is part of our "Conversation with a Colleague" series (see bit.ly/ATC-CWC). This essay, edited by Micheal Dent, is by Robin Glosemeyer Petrone, an architect with expertise in the design of acoustical space. Robin shares insights into her work and career as well as into her very important contributions to the ASA.

A major function of the ASA is in acoustical standards and so *AT* has had several essays on the program (see bit.ly/AT-Standards). In this issue, ASA Standards Manager Nancy A. Blair-DeLeon talks about the latest efforts in our standards program, with particular focus on education about standards.

This is followed by an essay by Shane Guan, Jill Lewandowski, and Erica Staaterman about the Bureau of Ocean Energy Management (BOEM). BOEM is a part of the US Department of the Interior that supports research on anthropogenic sound and marine life, particularly that associated with the development of offshore energy and mineral resources. This essay is part of an informal *AT* series on the agencies that provide funding to members of the ASA that started with an essay about the National Institute on Deafness and Other Communication Diseases (see bit.ly/AT-NIDCD). I invite representatives from other agencies, in the United States and abroad, that fund ASA members to contact me if they would like to discuss possibly having a similar essay in *AT*.

One way that the ASA supports many of its functions and many of its members is through the Acoustical Society Foundation Fund. The work of the Foundation is reported to members of the ASA annually in *AT*, and the 2022 report by James H. Miller, Fund chair, is in this issue. Jim uses the essay to highlight some of the recipients of various awards given out annually to members. A complete set of Foundation reports is at bit.ly/ATC-Foundation.

Several of the ASA technical committees host student competitions, and we are delighted share these with the *AT* audience, with a focus essays on the work of the winners and their projects. Thus, in this issue, we have an essay by Christina J. Naify and Michael R. Haberman about a student challenge in additive manufacturing. The descriptions of the winners and the brief videos that resulted in the awards show off three amazing young people who are the future of acoustics.

AT also hosts an annual article from the ASA Women in Acoustics (WIA) group (see past WIA columns at bit.ly/AT-WIA). In this essay, Tracianne B. Neilsen and Anna C. Diedesch focus on the value of involvement in the ASA in career development. They do this by featuring descriptions of two remarkable long-time ASA members, Alexandra Tolstoy and Fredericka Bell-Berti. Also note that Alex, besides be an outstanding scholar, is also a very fine water colorist. Her paintings have graced several *AT* covers, including the wonderful cover of this issue.

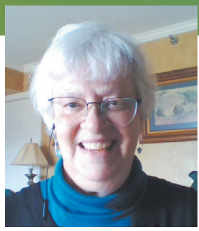
As many of you will know, we regularly have an *AT* intern, a young member of the ASA who wants to be involved in science communication. Each intern makes contributions in different ways. Our 2022 intern, Dr. Erik Alan Petersen, has been developing additions to "*AT* Collections," and he will be writing several essays about the value of study abroad as part of graduate or postdoctoral development. In the current essay, Erik talks about United States students working abroad for some or all their training. Many of our members will certainly "relate" to the experiences Erik describes. In a future essay, he will discuss the experiences of students coming to the United States for some of their training.

In our final essay, Ning Xiang and K. Anthony Hoover explore the history of ASA Fellows. In doing this, they examine the history of the Fellows program from its inception and provide a web link to a database of past Fellows.

I end by mentioning again the *AT* intern program. Interns are still in graduate school or newly out, such as in a postdoc or first acoustics-related professional position. Anyone interested in the 2023 intern position should drop me a note at apopper@umd.edu.

From the President

Peggy Nelson



As I write this article, fall has arrived in my home state of Minnesota. The State Fair has passed, and school has begun. Although you're reading this issue as we ease into winter, I'm writing it full of positive energy and anticipation for the fall season ahead. Among the topics on my mind are

- Our second cohort of undergraduate interns (SURIEA 2.0; see acousticalsociety.org/suriea) have ended their summer internships and have gone back to school or jobs enriched by the experiences they had with their mentors.
- We have an exciting Society conference in Nashville, Tennessee, with an impressive number of presentations (>950) on the program. A new partially hybrid conference mode is being tested and considered as we move ahead to the future of scientific conferences. We will try that again in Chicago, Illinois. We hope that you will make your voice heard to help shape the future of the Society and our meetings.
- Acoustics is in the news, demonstrating that our members are having a wide impact on science and society. Here are two examples.
    - Members such as Judy Dubno and Larry Humes have had an impact on public policy, such as this recent ruling opening up hearing aid access (see bit.ly/3ACkQwy).
    - Teams from Brigham Young University, Provo, Utah, with Kent Gee in the lead are measuring the sound levels of rocket launches, providing information about how "astronomically loud" rocket launches really are (see bit.ly/3x1gwGq).

All this is to say that I am exceptionally proud to be serving as the president of the Acoustical Society of America (ASA), and I'm extremely excited for the future.

Among the most exciting news in the Society is the formation of the ASA new Fund to Promote Inclusive Acoustics. This fund supports the inclusion and advancement of those who have been underrepresented in acoustics. The fund, approved by the Executive Council earlier this year, will support the Society's efforts to expand and diversify our membership and the discipline through outreach activities (such as SURIEA and other ideas to come) and through internal monitoring of barriers that prevent full inclusion of marginalized members. We're extremely proud of this bold move, and I encourage all members to consider two things: donating to the fund and bringing your new ideas for its use. Please see the announcement at acousticalsociety.org/foundation-fund.

We're also planning for the year ahead. Challenges will remain, no doubt, including stresses on our annual budget during times of likely inflationary forces. We're looking ahead to some possible long-term changes to our Society meetings, including, perhaps, the bold move of reducing the number of costly Society socials and lunches. The Executive Council is also considering a trial of a fully remote meeting, planned well in advance, that could increase access to those who cannot attend in person. We are learning, along with many other societies, that hybrid meetings are exceptionally challenging and frustrating. Thus, alongside our Nashville and Chicago trials of a few hybrid meeting sessions, we are considering this fully remote conference option, possibly as early as fall 2024. Please stay engaged and let us know your thoughts on such a trial.

We also recognize that when we choose a location for our in-person meetings there are political, economic, and social forces that affect our members' decisions about attending. This has come up around the Nashville meeting in particular. Our officers, Executive Council, and headquarters are considering these forces as we plan ahead. We may not be able to respond to every political issue that arises (who could have predicted these politically polarizing issues just a few short years ago?), but we must keep our members' safety paramount. We will continue to discuss these core values over the coming months as we plan ahead.

I look forward to seeing you again in person in Chicago (May 2023) where we will hold a postmeeting satellite workshop on diversity and inclusion for a group of related societies. Please watch for more announcements about this and join us if you are able. As always, I hope to see you on a webinar, at a committee meeting, and again in person soon. Let me know what you think we can do together.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Acquired Hearing Loss: Is Prevention or Reversal a Realistic Goal?

Colleen G. Le Prell

Noise exposure and aging are the most common causes of acquired hearing loss in humans. In addition, various workplace chemicals and prescription medications are toxic to the inner ear ("ototoxic") and result in hearing loss. Another possible auditory symptom produced by the same sources is tinnitus, a perception of ringing (or other) sounds "in the ears" (Spankovich et al., 2021).

Acquired hearing loss develops when sensory cells inside the inner ear are damaged. Resulting hearing loss is labeled based on the cause of the damage, including "noise-induced hearing loss" (NIHL), "drug-induced hearing loss" (DIHL), and "age-related hearing loss" (ARHL). In addition, hearing loss can develop suddenly with no known cause, in which case it is termed "idiopathic sudden sensorineural hearing loss" (ISSNHL). Some 30 to 60% cases of ISSNHL show spontaneous recovery, with the rest resulting in permanent acquired hearing loss (Montgomery et al., 2016).

In contrast to hearing loss that occurs with sensory cell loss, damage to the auditory nerve (AN) might make it harder to understand speech sounds or cause tinnitus (Kujawa and Liberman, 2015). Because these symptoms are not a hearing loss that can be measured using the traditional clinical "audiogram" test measure, these hearing deficits have been labeled "hidden hearing loss," even though they are not hidden to the patient (Schaette and McAlpine, 2011; Kujawa and Liberman, 2015).

Acquired hearing loss is a major public health issue affecting millions of people in the United States and globally. The past 20 years have included significant efforts to identify what biological events inside the inner ear occur during traumatic events such as noise exposure or ototoxic drug treatment. By identifying specific biological events that lead to the death of sensory cells in the inner ear, it has become possible to select experimental agents that might interrupt these events. Several experimental compounds that showed promise in successfully reducing NIHL, DIHL, or ARHL in preclinical (animal) models have been or will soon be tested in humans as possible inner ear medicines (Le Prell, 2021). Investigational medicines are tested in humans in clinical trials to determine safety, side effects, and effectiveness (Lynch et al., 2016).

Drugs that prevent acquired hearing loss could potentially prevent hearing loss that would normally develop in the absence of such drugs. However, these drugs would not benefit patients who have already developed hearing loss. For those patients, biological therapies that turn on cell development processes and drive development of new sensory cells are needed (i.e., medicines that enable missing sensory cells to be "regenerated"). Dramatic advances in regeneration therapies have been made, and the recovery of function may one day be feasible for those patients who already have acquired hearing loss.

This article first reviews how hearing is measured and the prevalence of acquired hearing loss based on epidemiological data. This is followed by a discussion of exciting advances in the development of investigational medicines for the inner ear. If successful within the regulatory testing and approval process, new inner ear therapies that prevent hearing loss or restore hearing function may one day be available to patients. Although much of this article focuses on threshold sensitivity, the audiometric gold standard (Ruben, 2021), it must be noted that speech communication is important to patients and tinnitus can be debilitating.

Normal Human Hearing

In the absence of ARHL, NIHL, DIHL, or other causes of hearing loss, the human auditory system is sensitive to frequencies from 20 Hz to 20 kHz, with the best sensitivity to sounds in the middle of this range, from

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approximately 250 Hz to 8 kHz. Sounds below 250 Hz or above 8 kHz must be presented at a higher decibel (dB) sound pressure level (SPL) to be heard. Perceptually, lower frequency sounds have lower pitches, like the rumble of thunder; higher frequency sounds have higher pitches, like a bird chirping. Patients with hearing loss are not equally affected across all sound frequencies, and ARHL, NIHL, and DIHL each have a characteristic pattern, with differences in the most affected sound frequencies. Clinical tests are used to document frequency-specific hearing loss.

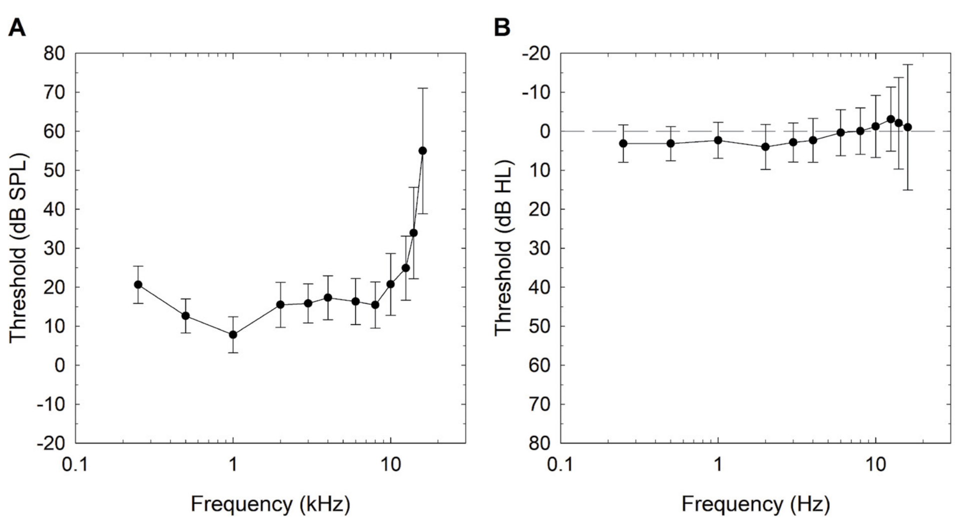
During clinical testing, an audiologist measures the lowest sound level that the patient reliably detects at different frequencies, with 0.25 to 8 kHz being the conventional test range. The lowest levels detected are the patient's "threshold" at each frequency, and these thresholds are plotted as the audiogram. The audiogram thus provides visual illustration of the quietest sound that can be reliably detected at each frequency.

The audiogram for a young adult with normal hearing is roughly "U-shaped," with the best sensitivity (lowest detection thresholds) within the conventional test range (0.25-8 kHz) and higher thresholds outside this range. The average threshold sensitivity for 66 normal-hearing young adult volunteers (27 male, 39 female, ages 18-29 years) tested by Spankovich et al. (2014) are shown in **Figure 1A**. Although frequencies below 250 Hz were not tested, the increased energy necessary for sound detection above 8 kHz is clear.

Clinical audiograms are not plotted as absolute sensory thresholds in decibel SPLs as in **Figure 1A**. Instead, they are shown as the difference between the patient's decibel SPL threshold and the reference equivalent threshold (RET) SPL as specified by the American National Standards Institute (2018). The decibel SPL threshold considered "normal" in the RET SPL is set as 0 dB hearing level (HL). Thus, a patient whose hearing matches the reference population has a 0 dB HL threshold at each frequency. Rather than the U-shaped audiogram, the young adult patient with normal hearing will have a flat audiogram.

To illustrate this, the thresholds plotted in **Figure 1A** are replotted in **Figure 1B** after conversion to decibel HLs. The average thresholds for the normal-hearing young adults are within 5 dB of the reference level at all tested frequencies. If a patient's hearing were poorer than the reference level, then their dB HL threshold would reflect the amount by which their hearing differs from the norm. Clinically, hearing loss is typically identified as "mild," beginning around 20-25 dB HL, and moderate, beginning

Figure 1. *Threshold sensitivity for 66 normal-hearing volunteers (27 male, 39 female, 18-29 years of age) tested by Spankovich et al. (2014). When plotted in decibel (dB) sound pressure level (SPL), the audiogram shows a roughly U-shaped form (**A**). When converted to dB hearing level (HL), the audiogram is flat (**B**). Values are means ± SD.*



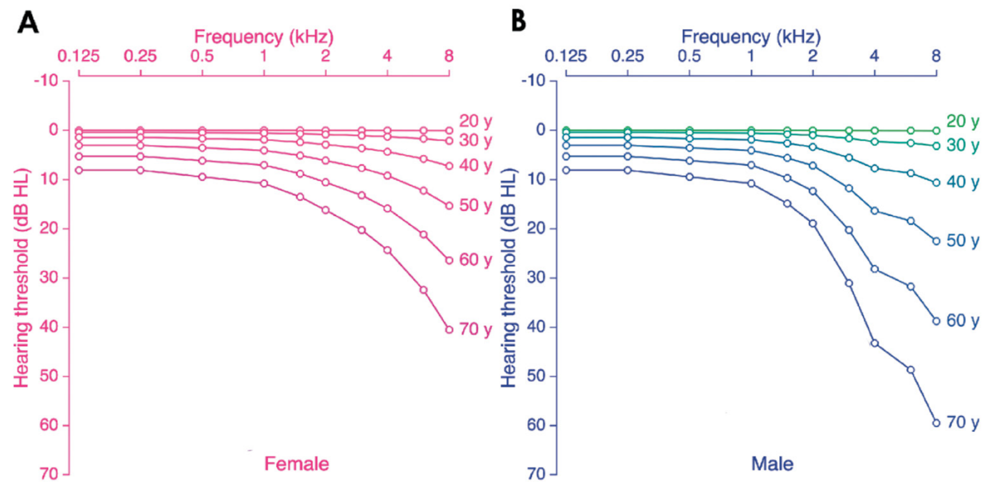


Figure 2. *Median age-related hearing loss (ARHL) for females (**A**) and males (**B**). ARHL is plotted as decibel HL where 0 dB HL is the reference level for normal-hearing young adults and ARHL is per the International Organization for Standardization (2017). Hearing loss increases from 20 to 70 years of age, with the higher frequencies affected first. Adapted from Wang and Puel (2020), licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0; creativecommons.org/licenses/by/4.0) license. Copyright 2020, Jing Wang and Jean-Luc Puel. Licensee MDPI, Basel, Switzerland.*

around 40-45 dB HL. Patients can have negative decibel HL thresholds, indicating that hearing is better than the reference level.

Age-Related Hearing Loss

Beginning at around 20 years of age, hearing slowly declines, with higher frequencies affected first and deficits progressing into the range of frequencies considered important for hearing speech (approximately 250 Hz to 4 kHz) as aging continues (see **Figure 2**). ARHL thus presents as a sloping hearing loss, with a greater hearing loss at higher frequencies than at lower frequencies; ARHL is pervasive in the US population. Based on nationally representative epidemiological data, about 50% of 50- to 59-year-old adults have high-frequency hearing loss (greater than a 25 dB HL average pure-tone threshold at 3, 4, and 6 kHz), increasing to about 75% of those age 60-69 (Agrawal et al., 2008).

At frequencies important for speech understanding, about 30% of 50- to 59-year-old adults have hearing loss (greater than a 25 dB HL average pure-tone threshold at 0.5, 1, 2, and 4 kHz), increasing to about 50% of those age 60-69 (Agrawal et al., 2008). This means that more than half of American adults over age 60 have hearing loss that can interfere with the detection of speech sounds.

The problem of untreated hearing loss is increasingly recognized as a major public health issue, with only about 20% of US adults with clinically significant hearing loss using hearing aids (Mamo et al., 2016). The high prevalence of hearing loss in combination with the low use of hearing aids suggests an urgent need for additional interventions, making medicines that would prevent ARHL of high interest (Wang and Puel, 2020).

Noise-Induced Hearing Loss

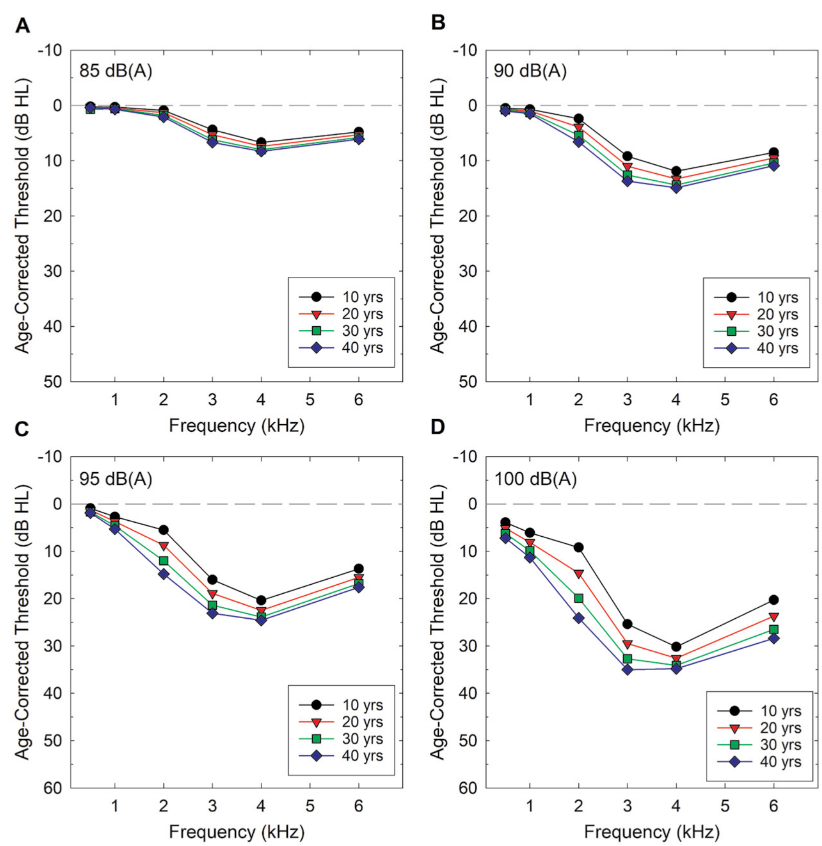
A working career can be some 40 years or so, and NIHL thus increases in parallel with ARHL developing across that same time span. NIHL occurs with any exposure long enough, loud enough, or repeated often enough to result in injury to the sensitive cochlear microstructures. NIHL typically presents as a "notched" audiometric configuration; a pattern of hearing loss in which thresholds at 3, 4, or 6 kHz are poorer than thresholds at lower frequencies (0.5 and 1 kHz) and 8 kHz. Words with energy in the affected frequency range, including for example words with the consonants "s," "f," and "th," may be affected first, with additional speech sounds becoming more difficult to detect or identify as NIHL progresses. Some 17% of the US adult workforce is exposed to hazardous workplace noise (Tak et al., 2009), and nearly 25% of US adults have a "notched" audiometric configuration

(Carroll et al., 2017). Thus, NIHL affects speech communication for millions of US adults.

Figure 3 illustrates "expected" noise-induced changes in hearing after subtracting expected ARHL for workers who are exposed to different amounts of noise for 8 hours per day. A-weighted decibels are decibel SPLs that have been "adjusted" as the US Occupational Safety and Health Administration (OSHA; 1983) requires for the measurement of workplace noise. Expected NIHL is illustrated for 8-hour exposures to 85 (**Figure 3A**), 90 (**Figure 3B**), 95 (**Figure 3C**), and 100 (**Figure 3D**) dB(A) exposures for durations of 10-40 years. Below 85 dB(A), occupational noise exposure is not regulated. Workers exposed to 85 dB(A) noise for 8 hours per day must be enrolled in a hearing conservation program and provided with hearing protection device (HPD) options, including earplugs or earmuffs. If workers are exposed to more than 90 dB(A) noise for 8 hours per day, they are required to use provided HPDs.

The data plotted in **Figure 3** come from tables provided by OSHA (1981) and include data collected before HPD use was regulated by OSHA. From the data in **Figure 3**, it is evident that significant occupational NIHL occurs within the first 10 years of exposure, with deepening and widening of the noise notch into additional frequency regions as exposure continues over the course of the 40-year working career. These patterns highlight the urgent need for interventions that effectively prevent NIHL. Although HPDs are highly effective when used consistently and correctly, NIHL associated with occupational exposure remains stubbornly persistent across industries (Themann and Masterson, 2019).

Figure 3. *Median noise-induced hearing loss (NIHL) after subtracting "expected" effects of age from the US Occupational Safety and Health Administration (1981) data tables for 85 (**A**), 90 (**B**), 95 (**C**), and 100 (**D**) decibel sound pressure levels (SPL), adjusting for A-weighted sound level as required by the Occupational Safety and Health Administration (1983). Adapted from Le Prell et al. (2022), with permission of Acoustical Society of America. Copyright 2022, Acoustical Society of America.*



Although **Figure 3** illustrates one set of expectations for age-corrected NIHL in workers, it must be noted that there is tremendous individual variation in the onset and progression of both ARHL and NIHL. This makes the precise division of hearing loss into ARHL and NIHL components difficult at the individual patient level. Multiple age-correction approaches are available (for a review, see Le Prell et al., 2022). The OSHA Technical Manual (OTM), which provides guidance on OSHA safety regulations, was completely revised and updated in 2021 (OSHA, 2021). One major change is that the updated OTM now refers to the age-correction factors of Flamme et al. (2020). Based on recent epidemiological data, these new tables allocate significantly less hearing loss to aging and thus more of the worker-observed hearing loss is attributed to noise.

Mechanisms of Pathology

Efforts to characterize the underlying pathology for NIHL, DIHL, and ARHL reveal that sensory cells and other important inner ear structures are damaged by noise, ototoxic drugs, and age-related breakdown, with pathology similar for all three types of loss. From a practical perspective, hearing loss identified as "ARHL" is not purely age related but rather reflects the accumulated loss of cells to both age-related breakdown and diverse microinjuries occurring across the life span. It is perhaps because of the overlapping patterns and mechanisms of cell death that experimental medicines have often shown a significant overlap in preventing NIHL and DIHL, albeit with more mixed findings for ARHL prevention.

Patterns of Cell Death and Cell Regeneration

One cell type long known to be highly vulnerable to noise, ototoxic drugs, and aging is the outer hair cell (OHC) of the cochlea (inner ear). If the OHCs are damaged, then NIHL, DIHL, or ARHL will develop; in other words, the normal audiogram shown in **Figure 1B** will change, shifting to look more like those shown in **Figure 2** in the case of ARHL or as a sum of the losses shown in **Figures 2** and **3** for a worker who is both noise exposed and aging. Readers are reminded that the hearing loss shown in **Figure 3** has been adjusted by values akin to those shown in **Figure 2** to illustrate NIHL after accounting for the expected ARHL.

Much of the above discussion has focused on the audiogram and detection thresholds. Patients are often concerned about sound identification in addition to sound detection. In other words, they can hear that speech is present, but they cannot sufficiently resolve the sound to understand the words. Subtle OHC damage is associated with deficits on hearing-in-noise tests (Parker, 2020).

Damage to other cells also compromises hearing in noise. Specifically, damage to inner hair cells (IHCs), a second type of sensory cell, or the AN fibers that carry sound information from the IHCs to the brain has recently been found to compromise the word understanding pathway (Grant et al., 2022). The IHCs and their connections with the AN are highly vulnerable to noise, drug, and aging injury (Liberman and Kujawa, 2017). Increased understanding of the importance of the IHC/AN pathway in speech understanding has created new inner ear drug targets in addition to those for the OHCs.

The past 15-20 years brought remarkable progress, with multiple new and fundamental insights into NIHL, DIHL, ARHL and the entire series of physiological events leading to cell death in the inner ear (Dinh et al., 2015). In parallel to improved understanding of cell death events, basic understanding of the molecular development of the inner ear has dramatically increased. The ability to deliver gene therapy or small molecule therapies that "reinitiate" developmental sequences that drive new cell division and development of those cells into new inner ear sensory cells has opened new doors to novel treatment approaches (Lewis, 2021).

Experimental Medicines for Hearing Loss Prevention

A wealth of basic scientific data show protection against NIHL, DIHL, and, to a lesser extent, ARHL, primarily within preclinical (animal) models. The data provide evidence of benefit for a variety of investigational medicines acting on different biochemical processes associated with sensory cell death. Data have been generated in diverse rodent models (rat, mouse, guinea pig, chinchilla) and in protocols that produce varied degrees of cochlear injury. Although the heterogeneity of experimental models precludes comparison of the relative benefits of different investigational medicines, the high rate at which positive results are reported highlights the promise that one or more investigational inner ear medicine will one day prove effective for human use. It is against this backdrop that one Special Issue was published in 2019 and a second

Special Issue will be published in 2023 in *The Journal of the Acoustical Society of America* (*JASA*).

The first *JASA* Special Issue, "Noise-Induced Hearing Loss: Translating Risk from Animal Models to Real-World Environments" (see bit.ly/3peiAXm; see introduction by Le Prell et al., 2019), addressed three specific themes: populations at risk for NIHL, models used in the preclinical testing of investigational inner ear medicines, and factors that influence individual risk for NIHL. Three human populations at significant risk for NIHL include workers exposed to occupational noise, military personnel, and musicians and other performing artists. Novel drugs are of particular interest for each of these populations, either because HPDs have not been broadly effective in protecting hearing for all who are required to use them (workers, soldiers) or because HPDs can prevent the user from hearing sounds that they need to hear to be effective in their jobs (soldiers, musicians, workers).

Clinical Assessment of Experimental Medicines

The second *JASA* Special Issue, "Noise-Induced Hearing Disorders: Clinical and Investigational Tools," provides comprehensive information about the measurement of noise-induced hearing deficits in clinical care and clinical trial settings. Although the audiogram in **Figure 1** is the clinical gold standard, diagnostic tests that identify the presence of specific noise-induced cochlear pathology provide additional tools for characterizing cochlear injury induced by noise, drugs, aging, or other injury process.

The second Special Issue explicitly addresses issues related to the selection of outcome measures and study end points in clinical trials investigating the prevention of hearing loss or restoration of auditory function. The audiogram is by far the most common outcome measure. A study end point is the specific analyzed parameter used to determine if the investigational treatment was effective. With the audiogram as an outcome measure, an audiometric end point could be a statistically significant reduction in the rate at which threshold shifts of 15 dB or greater are observed. If clinical trial participants receiving experimental medicine develop a hearing loss of 15 dB or greater significantly less often than the participants receiving an inert control (placebo), the audiometric end point would be accomplished.

Members of the public can learn about investigational medicines for the inner ear or experimental drugs being evaluated for other health conditions through ClinicalTrials.gov. Clinical trials under oversight of the US Food and Drug Administration (FDA) and clinical trials funded by the US National Institutes of Health (NIH) must be listed on this website. Clinical trials can also be voluntarily posted by study sponsors.

Role of the United States Food and Drug Administration

The FDA has a vast role in ensuring the safety, efficacy, and security of human and veterinary drugs, including biological products. The FDA prospectively reviews study outcome measures and end points when the clinical trial is submitted for review through the Investigational New Drug (IND) application process. It falls to the FDA to approve study end points that are ultimately used to determine if a drug is effective. Therefore, they must decide how much hearing loss is to be prevented for an investigational medicine to be deemed effective in preventing hearing loss. Similarly, they must determine how much hearing is to be recovered for a biological therapy to be deemed effective in restoring hearing.

Although the FDA would ideally have consistent standards for study end points, it must be recognized that expected hearing deficits vary widely from one clinical population to another. End points that are appropriate for one population may not be useful for a different population with a different pattern of hearing loss or a different time line for progression of hearing loss. It must also be remembered that not all clinical trials are under the oversight of the FDA. For those clinical trials that do fall under FDA oversight, the overarching goal is that study end points represent clinically meaningful benefits. The remainder of this article discusses outcome measures and study end points of interest for investigational inner ear medicine trials.

The Audiogram

The audiogram is by far the most common outcome measure for clinical trials evaluating prevention of NIHL, DIHL, or other forms of acquired hearing loss. Although the audiogram is almost universally used, audiometric end points differ significantly (Le Prell, 2021, 2022). As in studies using animal models, this makes it difficult to compare results across clinical trials completed to date.

Word Identification

Although the audiogram is the most common outcome measure (Le Prell, 2021, 2022), word identification in quiet and in noise are the most important functional measures for patients. Speech understanding is a key need, and about 10% of patients seek help for hearing-in-noise difficulties in the absence of any sound detection deficits (Parthasarathy et al., 2020).

The importance of speech communication to patients cannot be overstated. Communication difficulties and their impact on the quality of life were a key topic of discussion at the externally led patient-focused drug development (PFDD) meeting for people and families living with sensorineural hearing loss (Kelley et al., 2021). A PFDD is a structured meeting during which patients are invited to help the FDA and other stakeholders understand symptoms that matter most to patients, the impact of symptoms on daily life, and patient perspectives on therapies. The PFDD report for the meeting on sensorineural loss not only noted patient dissatisfaction with current hearing rehabilitation options but also the significant patient interest in and hope for regenerative therapies.

Difficulty identifying words delivered in quiet or against noise backgrounds is not captured by the audiogram. The term hidden hearing loss has therefore been used to describe difficulties understanding speech in noise (Kujawa and Liberman, 2015). Speech-in-noise measures have not routinely been included in clinical trials evaluating inner ear medicines to date (Le Prell, 2021, 2022), but their importance within the context of clinical trials is increasingly identified as important (Foster et al., 2022).

High-Frequency Hearing

Hearing at frequencies above 8 kHz has been described as important for music perception by musicians and other performing artists (Wartinger et al., 2019). Routine monitoring of hearing at frequencies above 8 kHz is therefore recommended for this population in the Santucci et al. (2020) guidance document. In the general population, measures of hearing at frequencies above 8 kHz will provide information about the function of the sensory cells in the inner ear regions that code those high frequencies, but whether damage to these regions will impact speech communication remains unclear (for a review, see Lough and Plack, 2022).

As discussed in the ***Role of the United States Food and Drug Administration***, the FDA is particularly concerned with clinically meaningful end points. Whether hearing preservation at frequencies above 8 kHz is clinically meaningful for some or all patients is thus an important question. This is a particularly important issue for DIHL and ARHL trials. Both DIHL and ARHL begin at frequencies above 8 kHz and progress to lower frequencies associated with speech communication over extended time periods. Protection of hearing above 8 kHz would be promising but does not necessarily assure that hearing at frequencies associated with speech communication will ultimately be protected.

Measures of Outer Hair Cell Function in Prevention and Regeneration Studies

Many regenerative therapies have the goal of OHC regeneration, although neural regeneration is also a goal (Lewis, 2021). The integrity of the OHC population can be evaluated by measuring distortion product otoacoustic emission (DPOAE) responses. DPOAEs provide a remarkably sensitive test of inner ear sensory cells using a miniature microphone inserted into the ear canal to measure nonlinear sound distortion elements (Lonsbury-Martin et al., 2017). DPOAE responses are only within the normal range if the OHC population is intact. Decreased DPOAE amplitude is observed if the OHCs are damaged or missing.

DPOAEs have been included in a few clinical trials evaluating investigational inner ear medicines, but, like high-frequency hearing, the clinical significance of DPOAE measures is uncertain. DPOAE amplitude will decrease with subtle OHC loss that is not yet sufficient to compromise threshold sensitivity as measured using the audiogram. This raises the possibility that DPOAEs could be considered a surrogate end point (i.e., a substitute measure that is expected to predict clinical benefit). On the other hand, DPOAE deficits are correlated with hearing-in-noise deficits (Parker, 2020), and the addition of hearing-in-noise measures might reduce the need for DPOAE surrogate measures of benefit.

To be clear, prevention of cell death is a positive finding. The crux of the issue with the use of DPOAEs in clinical trials is the extent to which the prevention of subtle injuries not yet noticeable to the patient/participant are clinically meaningful.

Measures of Inner Hair Cell/Auditory Nerve Pathway Regeneration

Seminal data from rodent models (Liberman and Kujawa, 2017) drove global interest in damage to the IHC/AN pathway and possible functional changes in humans with this pathology (Bramhall et al., 2019). A major challenge for human research is that there are no tests that specifically document the integrity of the IHC/AN pathway, although there are tests that measure the strength of electrical activity generated by the AN when it discharges in response to sound. Several datasets suggest that word understanding in quiet (Grant et al., 2022) and in noise (Grant et al., 2020; Mepani et al., 2020) is compromised when the IHC/AN pathway is inferred to be damaged based on decreased sound-evoked electrical activity of the AN. New data continue to emerge regarding tests for the integrity of the IHC/AN pathway in humans and provide growing evidence for age-related and, to a lesser extent, noise-induced pathology of the IHC/AN system in humans (Bharadwaj et al., 2022). Bramhall (2021) provides a careful discussion of the challenges of this type of work given that both OHC loss and the IHC/AN pathway pathology have the potential to impact neural measures and functional test results.

Summary and Conclusions

The topics reviewed here highlight the significant public health issue posed by acquired hearing loss, therapeutic insights gained through basic mechanistic inquiry, and the possible promise of both protective and regenerative medicine approaches. Clinical trials continue to emerge but do not yet provide clear insights into which experimental agents will be successful for which indications. New strategies better addressing acquired hearing loss are needed, hopefully including future FDA approval of safe and effective inner ear medicines. With success in clinical testing and FDA approval, new medicines could decrease the incidence and prevalence of acquired hearing loss, and regenerative therapies could decrease the impact of existing hearing loss. Despite the remaining challenges, major progress has been made, and there is good reason to believe that one or more experimental medicines will ultimately become new therapeutic options.

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U-boat Predators in the Great War: "A Problem of Physics, Pure and Simple"

Roy Manstan

That a solution to U-boat predation during World War I (WWI), also known as The Great War (1914–1918), was "a problem of physics, pure and simple" occurred in a conversation between British Nobel Laureate Sir Ernest Rutherford and American physicist Robert Millikan. Millikan then added: "It was not even a problem of engineering, although every physical problem, in general, sooner or later becomes one for the engineer" (Yerkes, 1920, p. 39). Technologies of the industrial revolution found new applications, many of which were about to converge on the battlefields of Europe. Scientists placed their discoveries into the hands of engineers, who then put their inventions into the hands of the military. The president of Western Reserve University (Cleveland, Ohio), Charles Thwing (1920, p. 115), was unequivocal: "The two new chief forms of attack, the submarine and the airplane, had their origins in the science of physics."

The War to End All Wars

Within weeks of Germany's onslaught through Belgium and Britain's declaration of war on August 4, 1914, H. G. Wells wrote *The War That Would End War*, pleading with the world to intervene: "There is no going back now to peace; our men must die, in heaps, in thousands; we cannot delude ourselves with dreams of easy victories" (Wells, 1914, p. 41). The title was soon popularized as *The War to End All Wars*.

As Wells had envisioned, the course of the war would become a four-year stalemate along the Western Front. European battlefields were overrun by mechanized infantry; the killing fields were made even more deadly with the introduction of rapid-fire weapons, poison gas, and bombing by aircraft. Long-range cannons bombarded Paris from 75 miles where targeting calculations included rotation of the earth.

Prior to 1914, none of the future belligerents understood the scale of devastation that The Great War would bring. Neither did they foresee the role of submarine warfare nor the need for effective anti-submarine technologies. This all changed on September 22, 1914. Germany's nearly obsolete Unterseeboot *U-9*, on a scouting mission in the North Sea, encountered three armored British cruisers. The reality of asymmetrical naval warfare arrived when *U-9*, with a compliment of only 29, fired torpedoes into the *Aboukir*, *Cressy*, and *Hogue*, sending the ships to the bottom with a loss of over 1,400.

Vulnerable to this invisible predator, a shocked and unprepared British Admiralty realized that The Grand Fleet was not so grand. Germany, however, immediately expanded submarine construction for extended operations into the Atlantic and Mediterranean. U-boats rose to periscope depth to aim and fire a torpedo, set to run below six feet, striking the soft underbelly of a ship. So-called "armored" vessels were only protected above the waterline against cannon fire, not against a well-aimed torpedo.

Allied destroyers, alerted to the presence of a U-boat by the explosive destruction of a merchantman, had one option, follow the trail of bubbles left by the torpedo and run through the U-boat's hull before submerging deeper than the destroyer's keel. Crude depth charges were available but were simply hit or miss. Once submerged and speeding from the scene, attacking the predator was futile. Time was better spent rescuing survivors.

"[T]he submarine problem was the problem of the war" (Millikan, 1919, p. 288), certainly the understatement of the war. From the start, however, naval planners understood a U-boat's vulnerability, and that is where our story begins.

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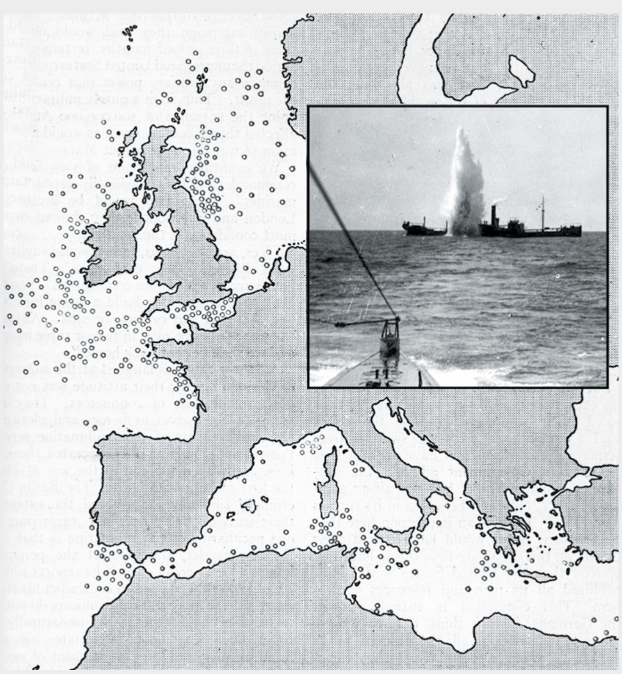
Urgent Need For Anti-Submarine Technologies

Admiral William Sowden Sims, commander of US Naval Forces in Europe, described the situation Allies faced (**Figure 1**) as "an enemy we could not see," adding "warfare upon the submarine was still largely a game of blind man's buff. If our men could not detect the submarine with their eyes, could they not do so with their ears. The enemy could make himself unseen at will, but he could not make himself unheard." Admiral Sims recognized the key to finding a solution to the "submarine problem" but only the key, not the solution itself. Sims (1920, vol. 39, pp. 357-358) set the stage: "[U-boats] produced sound waves that resembled nothing else in art or nature. It now became the business of naval science to take advantage of this phenomenon to track the submarine after it had submerged."

U-boats arrived on the scene in 1914, yet more than two-and-a-half years passed before the United States entered the war. Transforming the sounds of a submerged, transiting U-boat into a fatal vulnerability fell to the British. The Admiralty, unmoved by efforts from the scientific community to seek solutions, turned to a recently retired officer, Commander (later Captain) C. P. Ryan. Ryan left retirement in August 1914 and was assigned to an island naval base in the Firth of Forth, an estuary (Firth) of Scotland's River Forth flowing into the North Sea. The urgency of his assignment occurred in September when *U-21*, hunting British warships, entered the Firth. Recognized by the Admiralty during his prior service developing naval radio communications, Ryan was well suited to the task at hand, exploiting that U-boat vulnerability with electronic devices, microphones in particular. Beyond applications in undersea warfare, microphone-based acoustics also became essential on battlefields to locate and subdue enemy artillery fire (Costley, 2020).

Figure 1. *Locations of the vessels lost to U-boats in April 1917 (**open circles**), the month Admiral Sims arrived (Sims, 1919, vol. 38, p. 497). **Closed circles**, locations of small islands. **Inset:** British steamer* Maplewood *attacked by* U-35*, April 7, 1917. Reproduced from Wikimedia Commons, Bundesarchiv, Bild 102-00159 (bit.ly/3Vs2J68); licensed under a Creative Commons Attribution ShareAlike 3.0 Germany (CC-BY-SA 3.0, creativecommons.org/licenses/by-sa/3.0/de/deed.en) license.*



At the onset of WWI, the "hydrophone" was a technology that evolved in the late nineteenth century (see bit.ly/3RAIi5i). Not readily available in 1914, Ryan initially enclosed microphones in watertight housings and began "listening" for vessels operating in the Firth of Forth. The Admiralty, pleased with the results of his experiments, considered the pragmatic Ryan their golden child for submarine detection, a distinction he held throughout the war, to the chagrin of British scientists.

The British Board of Invention and Research

On February 18, 1915, Germany, having declared the waters around the British Isles a war zone, accelerated U-boat predation, increasing their range of operations. Open-ocean submarine hunting became a priority. Listening devices needed to become more sophisticated, focusing on range and bearing accuracy. Sir Arthur James Balfour, who had replaced Winston Churchill as First Sea Lord of the Admiralty, instituted a Board of Invention and Research (BIR). Balfour insisted that it be free of Admiralty control so it would draw in civilian scientists who could operate independently.

Meanwhile, Ryan continued to improve his hydrophone designs. He developed a shore station connected via cable to a bottom-mounted hydrophone. Initially in the Firth of Forth, shore stations were placed at the approaches to naval bases and high-value strategic locations. The Admiralty was delighted, establishing the Hawkcraig Experimental Station (described in Wilson, H. W., 1920) near the entrance to the Forth. Equally delighted, Ryan was provided with buildings, a staff, and vessels to conduct his system development, including the submarine *B-3*.

BIR scientists, however, were now in the game. Understanding the fundamentals of underwater acoustics became an important design tool, and Balfour began inserting civilians into the work at Hawkcraig. Ryan was not delighted with this influx of scientists. His lack of enthusiasm became evident in several communications between one of the civilian scientists, Albert B. Wood, and the BIR. He said this to Sir Ernest Rutherford: "[A]t the time of our arrival at Hawkcraig the state of our knowledge of underwater sound propagation in the sea was very primitive. [T]he serving officers at the station were not generally interested in the physical properties involved" (MacLeod and Andrews, 1971, p. 20).

When Admiral John Rushworth Jellicoe became the new First Sea Lord in November 1916, he created the Admiralty's Anti-Submarine Division (ASD), with directions to maximize research and development focusing on U-boat detection. Soon, the civilian scientists at Hawkcraig were reassigned to the Parkston Quay Experimental Station, allowing the BIR better access to vessels and facilities. Commander Ryan could now continue his approach to submarine detection unhindered.

Despite their differences, much was accomplished at Hawkcraig. The same Albert Wood who had complained to Rutherford was more generous when writing in 1962, citing examples of successful experiments. "Prior to the formation of the BIR, the Navy had not been very successful in their efforts to counter enemy submariners," Wood (1962) admitted, adding "on some experiments in August 1916 [at Hawkcraig], we located the [British] submarine *G.4* at a range of four miles."

Wood recognized that his colleagues at Hawkcraig learned much about sound source characteristics, but science was their role. Wood was less generous describing Commander Ryan: "Ryan's observations were empirical. He made no measurements," adding that Ryan "had made valuable initial progress in the art of listening underwater [but] knew little or nothing about the theory of sound or the possibilities of designing equipment" (Wood, 1962, pp. 10-14). There had been progress, but as 1916 came to a close, Admiral Jellicoe (1921, p. 49) lamented: "[The] hydrophone had been in the experimental stage and under trial for a considerable period, but it had not so far developed into an effective instrument for locating submarines."

Ruthless Submarine Warfare: America Enters the War

In February 1917, Germany announced a policy of *unrestricted* submarine warfare, declaring the waters "around Great Britain, France, Italy and in the Eastern Mediterranean" war zones, adding: "All ships met within the zone will be sunk" (Horne, 1923, vol. 5, p. 14). Although the possibility of the United States entering the war had been considered, the German Admiralty and Reichstag concluded that "there is no possibility of bringing the war to a satisfactory end without *ruthless* U-boat warfare" (Scheer, 1920, p. 247) (my emphases).

Triggering America's entry into the war, the Zimmerman telegram, intercepted by the British in January 1917, was intended to create an alliance between Mexico and Germany, claiming that "employment of ruthless submarine warfare now promises to compel England to make peace in a few months" (Horne, 1923, vol. 5, p. 43). On April 2, 1917, US President Woodrow Wilson addressed Congress, emphasizing Germany's use of submarines, adding that vessels "have been ruthlessly sent to the bottom without warning and without thought of help or mercy for those on board" (Horne, 1923, vol. 5, p. 108). Four days later, in a joint resolution, America declared war on Germany.

Americans, even those who wished for neutrality, knew that war with Germany was inevitable. Preparations began soon after the sinking of *Lusitania* in May 1915 (see bit.ly/3Ps8SLX), with the loss of 128 Americans. US Secretary of the Navy Josephus Daniels envisioned having a small group of industrial experts consider approaches to solving the "submarine problem." In July, Daniels contacted Thomas Edison to head what would become the Naval Consulting Board (NCB). During an October meeting, one of Edison's engineers stated that: "[I]t was [Edison's] desire to have this Board composed of practical men who were accustomed to doing things, and not talking about it." Edison later "privately advised Daniels that he did not think 'scientific research' would be necessary to any great extent" (Kevles, 1978, p. 106).

There was no room for scientists in the NCB, and that upset members of the US National Academy of Sciences.

George Ellery Hale, in particular, was certain that President Wilson would welcome assistance from the Academy. It was not until June 1916 that plans were underway to establish a National Research Council (NRC). Members of the Academy crossed the Atlantic to discuss wartime issues with their European counterparts, the information gained being presented at the initial NRC meeting in September (Millikan, 1950, p. 126). Science would now have a role in solving the "submarine problem."

The NCB would provide the inventive know-how; the NRC would apply scientific principles. But that had not worked in Britain where Ryan, the pragmatic inventor, vied with the BIR scientists, a situation that Secretary of the Navy Daniels was aware of. Daniels sought a working relationship between the NCB and NRC, realizing that cooperation would have to be mandated. That June, Daniels formed the Special Board on Anti submarine Devices, led by an admiral with civilian and military members. "The department [of the Navy] has approved the plan to coordinate and organize the efforts of various groups now considering submarine and anti-submarine devices," adding that the Special Board "shall have complete charge of the carrying out of experiments on submarine and anti-submarine devices" (Scott, 1920, p. 82).

The Navy Establishes Experimental Stations

By early 1917, the NCB received authorization to create an experimental station at Nahant, Massachusetts, on a peninsula extending into Boston harbor. Laboratory facilities were completed on April 7, with an engineering staff from General Electric, Western Electric, and the Submarine Signal Company. A scientific mission from Europe, primarily England and France, arrived in Washington in June to share anti-submarine concepts at meetings with American scientists and engineers. Technologies included passive listening, echolocation, and electromagnetic systems.

At the beginning of July, NRC members met in New London, Connecticut. Soon thereafter, the Naval Experimental Station was established on the grounds of Fort Trumbull near the entrance to the Thames River in New London. Throughout the war, the scientific and engineering staff was drawn from multiple universities. Those remaining at armistice are shown in **Figure 2**. Work at the Nahant and New London stations began immediately, expanding on many of the ideas from the June meetings with European scientists. With

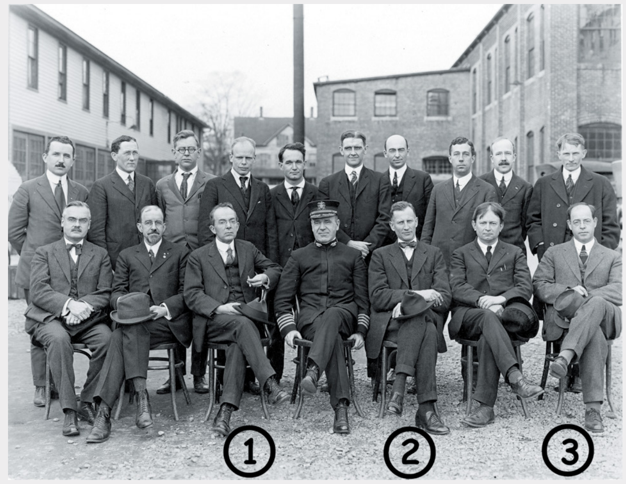


Figure 2. *Naval Experimental Station scientific staff at Armistice, three of whom are referred to in this article: 1, Ernest Merritt; 2, Max Mason; 3, Harvey Hayes. Courtesy of the Harvey Hayes Family archive.*

oversight by Daniels' Special Board, science and technology could, and would, be blended together.

It is impossible, within the limits of this article, to fully describe the extent of the innovation from these experimental stations, but here is a summary. For details, see Manstan, 2018.

Binaural Listening and Broca Tubes

When Sir Ernest Rutherford addressed the June meeting in Washington, he brought an example of the Broca tube, describing its use in binaural listening. One of the attendees, H. A. Wilson, wrote: "[The Broca tube] consisted of a flat circular metal box, one of the circular sides of which was made of a thin metal plate. A tube fixed to the center of the opposite side led to the ears of the observer" (Wilson, H. A., 1920, pp. 178-179). Referred to as an "acoustic receiver," the Broca tube was readily adapted to passive listening.

What finally emerged after initial experimental successes at Nahant and New London was the binaural C-tube, an easily constructed device that "any plumber's helper could have duplicated" (Thompson, 1937, p. 59). Initially installed on 110-ft vessels designed specifically for U-boat hunting, submarine chasers (or subchasers) (see Woofenden, 2006) became essential to the anti-submarine effort. The C-tube (and SC-tube) was a T-shaped device mounted through the hull and lowered below

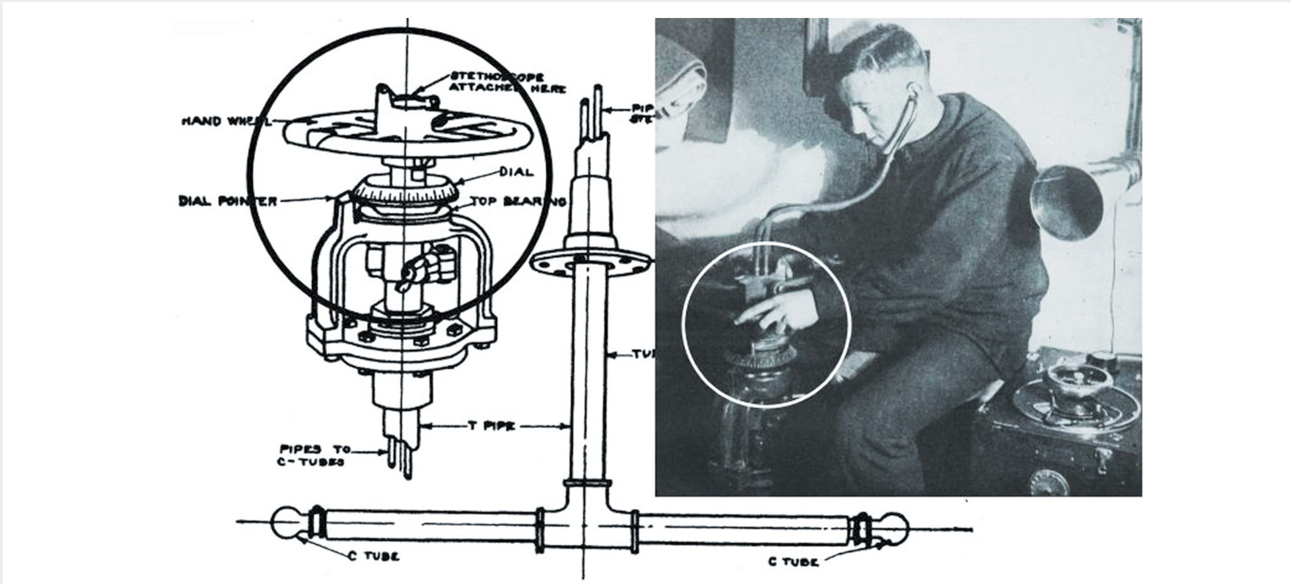


Figure 3. *With the subchaser at rest, the C-tube (Hayes, 1920, p. 30) was lowered below the keel (**left**) and rotated until the listener received equal sound levels in each ear (**right**). The bearing to the source relative to that of the subchaser was indicated on the dial (Sims, 1920, vol. 39, p. 355).*

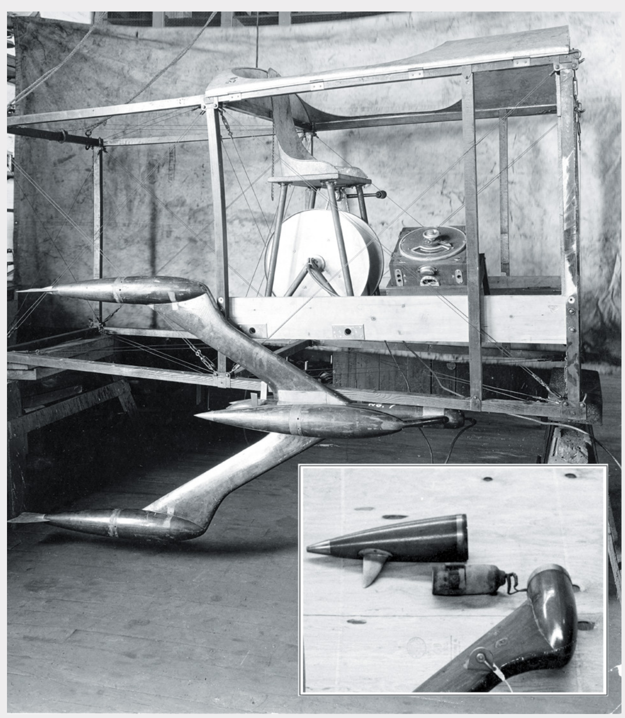
the keel. A Broca tube receiver was placed at each end of the "T" at a separation based on the speed of sound in water re-creating in-air human binaural hearing. The thin metal Broca tube plates were replaced with rubber spheres, the underwater sounds transmitting more efficiently into air-filled metal tubes and eventually to the stethoscope worn by the listener (**Figure 3**).

Acoustic receivers based on the Broca tube remained common on many vessels operating in the war zone. An MV-tube design by Max Mason was composed of a line of multiple Broca tubes. Tested on destroyers and along the keel of a submarine, the device functioned with the ship underway (see Mason, 1921). Mason was sent to England and France to oversee their installations.

Hydrophone-Based Listening Devices

By 1917, multiple hydrophone designs were in use by all countries in the conflict. The choice was resonant (used by Germany and initially by Ryan) or nonresonant. The advantage of a resonant hydrophone was that if the sound source was at that resonant frequency, a U-boat could be detected at greater distances. Nonresonant hydrophones, in general use among the Allies but needing electronic amplification, were sensitive over the broad range of frequencies associated with submarines.

Figure 4. *The streamlined shape of this three-element OV-tube enabled towing by a blimp. A hydrophone was housed at the end of each wing and at the tow point. **Inset:** one of the wing tips disassembled, exposing the hydrophone. See Manstan (2018) for this image and a variety of listening devices.*



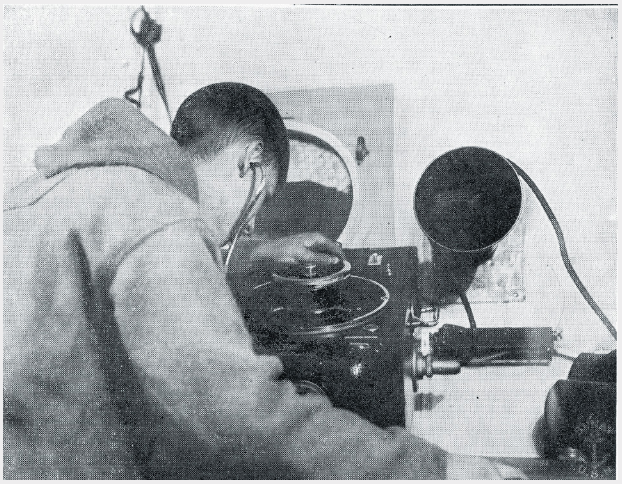


Figure 5. *A subchaser listener is shown at the handwheel of a K-tube compensator. The bearing was passed to the bridge via the speaking tube on his right (Stockbridge, 1920, p. 221).*

Prior to World War II (WWII), passive detection technologies were referred to as "listening devices" and the operators "listeners." Also, the word "tube" of Broca tube receivers became standard for all passive devices, even after hydrophones where the air-backed tubes were replaced with wires were employed. The first of those was the K-tube.

The K-tube was composed of a triangular frame with a hydrophone at each corner. Lowered from a subchaser while the vessel drifted in the current, the engines were shut down to eliminate the vessel's own noise. The listener switched between pairs of hydrophones, the loudest pair indicating within which 120° sector the U-boat was transiting. This three-element system proved effective, and multiple variations were created; there were OV-tubes (**Figure 4**); OK- and OS-tubes; and PB-, Delta-, X- and Y-tubes, some designed to be towed by a destroyer or a blimp. A three-element, bottom-mounted shore station system was also used. None, however, used a tube.

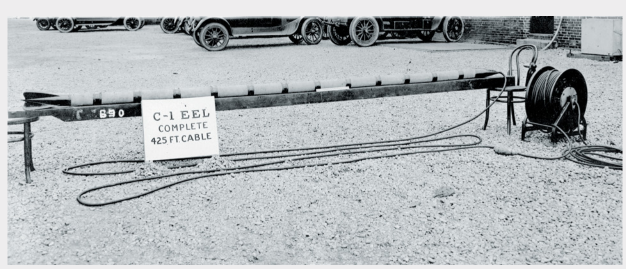
Prototype systems tested at Nahant and showing promise were sent to New London for further development. Determining an accurate bearing to within 5° was essential, requiring an additional technology, a compensator. Regardless of the device, a listener had to make adjustments with the compensator such that sounds, transmitted acoustically or electronically, would reach both ears in phase (see Manstan, 2018, chs. 19-20).

For Broca tube systems, underwater sounds arrived at the listener's ears via an air path. Hence in multireceiver, nonrotatable systems, each air path had to be adjustable. Compensator air paths were lengthened or shortened along circular grooves on plates within a housing. The listener turned a handwheel; the amount of rotation needed to equalize the path lengths provided an indication of bearing. For hydrophone systems, turning the handwheel added electronic time delays between sensors equalizing the phase, with bearing indicated on the listener's compensator. In either case, the listener passed the relative bearing to the vessel's captain and navigator (**Figure 5**).

Towed Line Arrays

The desire for towable systems became another priority at New London. The result was a 12-element flexible line array, referred to as an electric eel or simply an eel (**Figure 6**). Line arrays were tested on seaplanes that would taxi on the surface and on blimps that could move along a few feet above the surface, but the most promising application was towing from the stern of a destroyer. A pair of eels could account for the left/right ambiguity associated with omnidirectional hydrophones. The British designed baffles for their single-element devices, rotatable mounts providing directionality within a streamlined tow body. American hull-mounted port- and starboard-mounted arrays depended on the hull serving as a baffle.

Figure 6. *During the closing months of the war, Harvey Hayes was evaluating towed arrays at New London, Connecticut, and on September 21, 1918, wrote: "Comparative tests between C-1 eels and O-S and O-V and O-X tubes on a slow-moving submarine as a sound source showed that the eels were superior as a detecting device. The observations are taken more rapidly and with less interference from other boats. The eels also outranged any of the listening devices with which it was compared. Selectivity proved comparable to MV [Broca tube] lines on [the test ship]* NARADA.*" Courtesy of the Harvey Hayes Family archive.*

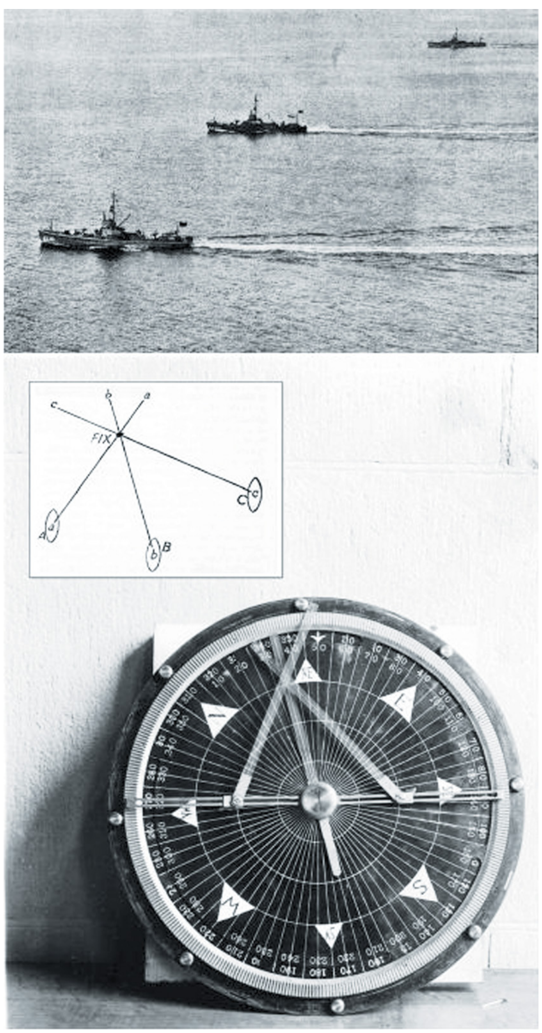


America, Ready to Join The War

The work at the Naval Experimental Station had progressed 24/7 for 6 months. Subchasers began arriving at New London that fall. Crews received rigorous training in Long Island Sound (south of the Connecticut coast) where seasonal winds created conditions close to those in Europe. By December 1917, prototype listening devices were in the English Channel hunting U-boats.

The Special Board was also responsible for ensuring that devices deployed to the war would survive harsh combat operations. Station staff who were designing the devices were therefore required to join the listeners when training at sea. "In those days," proclaimed subchaser commander Ensign George Wallace, "few of us had our sea stomachs and many a seaman locked arms with a civilian inventor or two over the rail" (Nutting, 1920, p. 85). The listeners, two per vessel, had to be well prepared. "To qualify as a listener it was necessary to locate the direction of a submarine within five degrees. Practice tests were made daily to familiarize the students with various noises encountered" (Bean, ca. 1920). Listeners had to distinguish the target among multiple underwater sounds.

Figure 7. ***Top:*** *hunting unit en route to its search area.* ***Bottom:*** *bearings were set on the position plotter.* ***Inset:*** *where they crossed indicated the location or "fix" on the target.* ***Top*** *and* ***inset*** *from Sims, 1920, vol. 39, pp. 362, 458; position plotter, courtesy of the Harvey Hayes Family archive.*



By February 1918, convoys of subchasers began the 12-week Atlantic crossing, arriving at bases in England, Ireland, and the Greek island of Corfu at the entrance to the Adriatic. Subchasers operated in hunting units of three (**Figure 7**), two wing boats and the central flagship. When a U-boat was detected, each subchaser radioed bearings to the flagship navigator. The hunting unit now had both elements for targeting, bearing *and* range.

An example of a U-boat hunt (**Figure 8**) is from an Office of Naval Intelligence (1918) report. The 30-hour chase ended when listeners heard unfamiliar sounds, as recounted by Admiral Sims: "[A]t about five o'clock on the afternoon a sharp piercing noise came ringing over the [hydrophone] wires. It was a sound that made the listeners' blood run cold. In all, twenty-five shots came from the bottom of the sea. As there were from twenty-five to thirty men in a submarine crew the meaning was all too evident. Nearly all of them had committed suicide" (Sims, 1920, vol. 39, p. 468).

Armistice and The War That Did Not End All Wars

In a postwar interview, Frederick Körner, an officer on *U-155*, made this observation: "the wide expanse of the Atlantic was not enough to keep us from the coast of far-off America. To those who can see into the future, surely this is a warning of what later wars may bring" (Thomas, 1928, p. 332).

With expectations on both sides that the conflict would continue another year, a number of anti-submarine technologies were nearing readiness for deployment. In October 1918, a conference was held in Paris to discuss the use of supersonics (a term commonly used at that time), already considered for active echo detection by

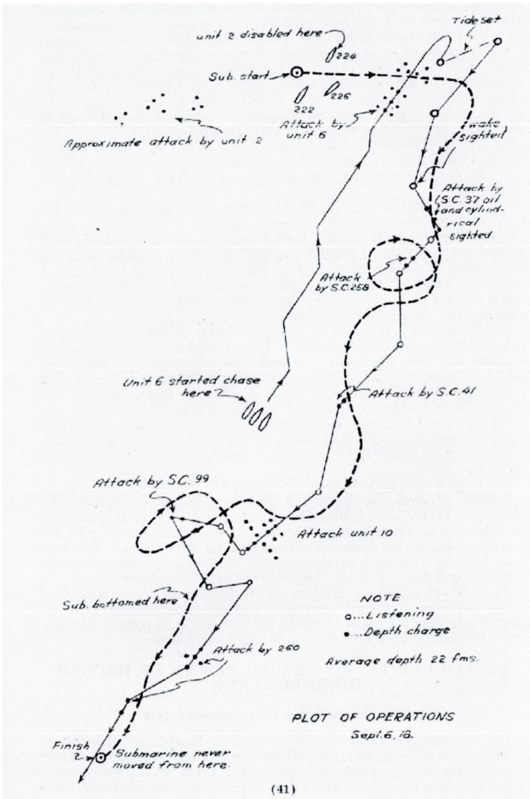


Figure 8. *On September 6, 1918, listeners detected a U-boat operating within the English channel (**top right**). **Dashed line:** path of the U-boat attempting to evade the subchaser units (**solid line**) (Office of Naval Intelligence, 1918, p. 41).*

the Americans, British, and, in particular, French Professor Paul Langevin. He had been experimenting with piezoelectric transmitters at Toulon, France, receiving an echo from a submerged submarine at a range of one mile. What was also discussed among the scientists in attendance, however, was the need for increased knowledge of the properties of seawater affecting sound propagation, specifically "the viscosity of the water, its temperature, the presence of marine life and debris" (Weir, 1997, p. 88).

Armistice occurred at the 11th hour on the 11th day of the 11th month in 1918. Many of those whose monumental effort of science and innovation defeated the U-boat, continued to imagine a dangerous future as prophesized by Körner. On November 9, Ernest Merritt briefed the Special Board on Antisubmarine Devices, recommending systems that should continue to be pursued, one in particular: "Echo methods whether using waves above the audible range or, if practicable, longer waves," stressing that "the development of antisubmarine devices should continue even after peace is declared with the idea of obtaining such devices as will make it extremely difficult for submarines to be used in the future." In a postwar briefing (December 27, 1918), Merritt again looked to the future, concerned about the "echo method" and if "some material might be found which absorbs underwater sound waves as completely as black paint absorbs light" (Merritt, 1917–1918).

The Great War was not the war to end all wars, as H. G. Wells had hoped in 1914. Only two decades passed before Germany's intentions toward Europe rose again. In the summer of 1939, U-boats returned to a policy of unrestricted submarine warfare, approved by Germany's Chancellor Adolph Hitler.

Acoustics Today [Well, Almost]: World War II and the Cold War

It is thought that there are six degrees of separation between any two humans on the planet. When warfare technologies are involved, the degrees of separation between warfare system designers and the warfighters must be reduced to zero.

This essential collaboration reappeared during WWII when ASW was the mission of another generation of civilian scientists. Fort Trumbull in New London became the home of the Columbia University Division of War Research, while another group, the Harvard Underwater Sound Laboratory, was established in Cambridge, Massachusetts. On the US West Coast, San Diego hosted the University of California Division of War Research. Active and passive submarine detection devices, now "sonar," evolved at these research centers throughout WWII. Submarine warfare was far more lethal than in the past; yet once again, it would take scientists and engineers to turn the oceanic predators into prey.

In 1946, sonar development by Columbia and Harvard was consolidated in New London to form the United States Navy Underwater Sound Laboratory. Soviet submarines had to be detected at ranges and depths far exceeding the U-boats of WWI and WWII. The October 1918 conference in Paris predicted the inevitable, that to exploit the physics of underwater sound, the properties affecting propagation had to be studied and incorporated into Cold War sonars as, for example, that of sonar pioneer Thaddeus Bell (2011) and the SQS-26 surface ship sonar. See Manstan (2014) for an overview of Cold War ASW technologies developed in New London and operational within the fleet from a field engineering perspective.

Then and Now

This from Sir Ernest Rutherford in 1918: "If the Navy is to retain its supremacy in the future, methods must be devised for systematic scientific investigations [between] Naval Officers who have shown marked scientific ability [and] highly trained and technical civilians" (MacLeod and Andrews, 1971, p. 35).

Maintaining the Navy's supremacy into our future, dominated by antisubmarine technologies, require those same systematic scientific investigations involving knowledgeable civilian and naval staffs. Nuclear-powered submarines dive deeper, move faster and quieter, remain submerged longer, and will continue to be a technological challenge to locate in a three-dimensional undersea battlespace.

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Roy Manstan began his field engineering career in 1967 at the US Navy Underwater Sound Laboratory, retiring in December 2005 from the Naval Undersea Warfare Center. He received degrees in mechanical engineering from Lafayette College, Easton, Pennsylvania (BS) and the University of Connecticut, Storrs (MS) and in zoology from Connecticut College, New London (MA). Qualifying as a Navy diver in 1974, he was later appointed command diving officer, working with antisubmarine warfare technologies worldwide. After retirement, he volunteered at Old Saybrook High School, Old Saybrook, Connecticut, creating a working replica of the Revolutionary War submarine *Turtle*. Photo shows him emerging through its hatch (Manstan and Frese, 2010).

The Acoustics of the Modern Jazz Drum Kit

E. K. Ellington Scott and Andrew Morrison

Introduction

Other than the human voice, there is likely no musical technique older than using percussion to produce rhythmic beats (Morley, 2013). Anthropologists and historians have described possible scenarios where ancient people created rhythmic sounds by either striking their bodies, stamping their feet, or through the repeated striking of tools on stone or wood (Blades, 1992; Montagu, 2002). The earliest examples of percussion instruments crafted by people include rattles, rasps, and shakers that were used rhythmically.

The modern percussion family has grown well beyond simple rhythmic instruments. Some percussion instruments are tuned to musical pitches for melodic or harmonic purposes. However, many percussion instruments do not have a definite pitch. In general, the more harmonic the peaks in the spectrum are, the easier it is for us to hear the sound as having a definite pitch.

In this article, we first examine the differences between drums with and without definite pitch. We then trace the historical and technical development of the components of the modern jazz drum kit. For an example of a jazz drum kit, see youtu.be/sKbk1LcsuUM.

Frame Drums

The frame drum, one of the simplest drum types, does not have a definite musical pitch. It is constructed by stretching a thin, flexible membrane over a rigid hoop (see youtu.be/LF7ybVKX2p4). A frame drum's sound can be varied by changing the size of the drum, the mass and stiffness of the drumhead, how tightly the drumhead is stretched, and the technique used to play the drum (see **Multimedia File 1** at acousticstoday.org/scottmedia). Throughout history, frame drums have been used in musical traditions worldwide. Evidence of their use has been found in Mesopotamia dating as far back as ca. 3000–2700 BCE (Blades, 1992).

Striking the drumhead of a frame drum, whether by hand or with a beater, causes the drumhead to oscillate. Most frame drums are sufficiently small such that the effect of air loading on the drumhead is small. Therefore, the drumhead vibrates near frequencies corresponding to the ideal modes of vibration of a stretched membrane. Each mode vibrates not only at a particular frequency but with a unique pattern called a mode shape.

The mode shapes of a uniform membrane can be predicted by solving the wave equation in cylindrical coordinates, a mathematically complex process. What is important, however, is that the predicted modal frequencies are not integer multiples of the lowest mode. The solutions predict all the resonances of the drum. Depending on where the drummer hits the drumhead, the resulting motion of the drumhead is a combination of all the vibration modes, each with their own amplitude and phase.

The first 12 mode shapes for a stretched membrane are shown in **Figure 1**. The mode shapes are characterized by the location and number of lines or circles where minimum vibration occurs. Whereas a one-dimensional standing wave (such as a tautly stretched string) has points of minimum vibration called nodes, the two-dimensional standing waves refer to the lines or circles of minimum vibration as either nodal lines or nodal circles. For the circular membrane, the lines are often referred to as nodal diameters because the line bisects the circular membrane. The notation (m,n) labels the mode shapes according to the number of nodal diameters (m) and number of nodal circles (n). Regardless of how the drumhead is secured to the frame drum, the drumhead will be held in place at the rim. Therefore, each mode of

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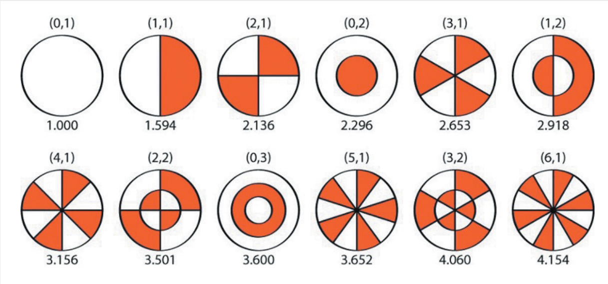


Figure 1. *First 12 modes of vibration of a circular membrane. The nomenclature [(*m,n*); above each mode shape] is used where m denotes the number of nodal diameters and n denotes the number of nodal circles. The ratio of modal frequency to frequency of the lowest mode is below each mode shape.*

vibration has at least one nodal circle located at the rim. The ratio of the mode's frequency to the frequency of the lowest mode is shown below each mode shape. For example, a drum having a frequency of 100 Hz for the (0,1) mode would be expected to have a frequency of around 159 Hz for (1,1) mode because 100 Hz multiplied by 1.594 is close to 159 Hz. The (2,1) mode would be expected to be close to 214 Hz because 2.136 multiplied by 100 Hz is close to 214 Hz. The modes for this type of drum are not harmonically related so there is no definite pitch associated with the sound of the drum.

Drums with a Definite Pitch

On being struck, frame drums (and many other drums) do not have a specific pitch associated with their sound. Although such drums can be tuned to sound that is relatively higher or lower, a listener would not associate the sound of the drum with a specific musical note. At the same time, some exceptions exist of pitched drums that are tuned such that they are played with a definite pitch. A few examples that we discuss here are the mridangam, tabla, and timpani.

Mridangam and Tabla

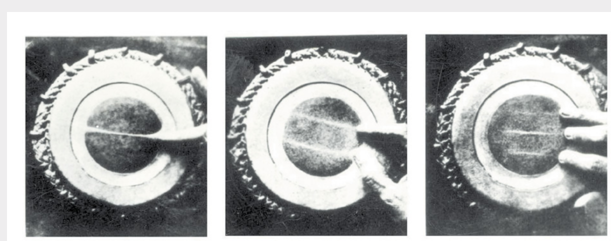
The mridangam and tabla drums from India are some of the most studied pitched drums. The mridangam (see **Figure 2,** *left*) is a long barrel-shaped drum with drumheads of differing sizes on opposite ends. It is used in Carnatic music traditions common in South India (see youtu.be/AI9RJbljBLw). The tabla (**Figure 2,** *right*) is a single instrument that consists of two single-headed drums of different sizes. It is used in Hindustani classical music and originated in North India (see youtu.be/r31oe7Sm0vI?t=10).

What makes the Indian drums acoustically interesting is that the drum makers apply several layers of a paste to the center of the drumhead that brings the first five overtones into harmonic alignment. The dried paste is seen in **Figure 2** as the central dark circular patch on each drumhead. Because there is a strong harmonic series of the first five partials, the sound of these drums is recognizable as a definite pitch. The acoustics of these drums were studied in detail by the Nobel laureate C. V. Raman who was the first to write about them in a scientific journal (Raman and Kumar, 1920). Mode shapes from his later work (Raman, 1935) are shown in **Figure 3**.

Raman sprinkled fine-grained sand on the drumhead before the drum was struck. On hitting the drumhead,

Figure 2. *The mridangam (**left**) is an Indian drum held in the drummer's lap and played while the drummer is seated. The tabla (**right**) is an Indian two-drum instrument usually performed with the drummer sitting on the floor and the drums in front of the performer, who is also on the floor. The drumheads are layered with a paste designed to tune the drumhead modes harmonically. Tabla image reproduced from Wikimedia Commons (see w.wiki/5aPC), licensed under CC BY SA 4.0 (see creativecommons.org/licenses/by-sa/4.0). Author http://muzyczny.pl.*

Figure 3. *Mode shapes of the mridangam or tabla drumhead. Fine-grained sand was sprinkled on the drumheads. On striking, the grains moved to nodal lines where the motion of the drumhead was at a minimum. Reproduced from Raman (1935), with permission of Springer.*



sand grains gathered at the vibrational nodal lines. Raman found that he could excite different modes by changing where the drum was struck. For some of the shapes, holding his fingers at the location of a nodal line allowed that mode to be revealed.

Although much of the early studies of Indian drums focused on mass loading the membranes to form a harmonic spectrum, recent work on the tabla has shown that the air inside the drum also affects the harmonicity of the sound (Tiwari and Gupta, 2017). The air-loading effect is greater for the left-hand tabla drum, the larger of the pair.

Timpani

A pitched drum used both rhythmically and at least somewhat melodically is the timpani. The timpani is recognizable as the large drum used by orchestras having a kettle-shaped bowl over which the drumhead is stretched. A single timpanist in an orchestra may play from three to six timpani, each tuned to a particular pitch (see **Multimedia File 2** and **Multimedia File 3** at acousticstoday.org/scottmedia).

A pedal at the timpani's base allows for tuning the drum via an internal mechanism that uniformly adjusts the tension of the drumhead. The drums are tuned to specific notes for each musical piece performed, and it is not uncommon for the timpanist to retune one or more drums during the performance of a piece.

The acoustics of the timpani has been studied since Lord Rayleigh's time. The timpani has a definite pitch because the lowest several modes of vibration are in harmonic alignment. Looking at **Figure 1**, it is not apparent how this could be possible. However, several factors contribute to giving the timpani its pitch.

Foremost is that the air above the drumhead provides a significant load that lowers the frequencies of the vibration modes. Rayleigh first identified that the pitch of the timpani originates from the (1,1) mode and not the lower (0,1) mode. Because the two antinode regions of the (1,1) mode move with opposite phases, the movement of the drumhead causes the air above it to slosh back and forth.

Another factor affecting the sound of the timpani is that only the modes with the single nodal circle (located at the rim) contribute significantly to the sound spectrum. Modes with nodal circles in the middle of the drumhead tend to decay quickly. Also, the timpanist affects the deemphasis of these modes. By striking the timpani about a quarter into the center, the excitation point is close to the nodal circle of several modes, so these modes are not strongly excited.

Finally, as seen with the tabla, the air inside the kettle also influences the drumhead resonances. Internal air loading of the drumhead is responsible for fine tuning of the frequencies, but it is a measurable effect.

Measurements of a 26-inch timpani showed that the (1,1), (2,1), (3,1), (4,1), and (5,1) modes had frequency ratios of 1.00:1.50:1.98:2.44:2.91 (Christian et. al., 1984). This set of ratios is close to 1:1.5:2:2.5:3. By multiplying the ratios by a factor of two, they are seen to be the same ratios as 2:3:4:5:6. Because of the harmonic nature of these modes, we are able recognize the definite pitch of the timpani.

History and Acoustics of Drum Kit Instruments

One of America's first musical inventions was the drum kit. This hybrid instrument consolidated its pieces from around the world into a rhythmically mesmerizing voice. The pieces making up a drum kit include drums, cymbals, and a myriad array of auxiliary instruments. Drums used in a drum kit include snare drums, bass drums, and toms, all of which are cylindrical drums with a drumhead on each side.

We first explore the maturation of the drum kit due to social and cultural influences, percussionist ingenuity, and stylistic development. Then we examine the acoustics of the most common drum kit components.

Evolution of the Modern Jazz Drum Kit

Before discussing the evolution of the modern drum kit, we must examine the historical and cultural foundation leading to its creation. We explore how African and Middle Eastern diasporas, improvisation, and immigration all contributed to the development of the drums in Western European societies and, specifically, the drum kit in the United States.

The snare drum, bass drum, and cymbals are the foundational percussion instruments of the drum kit. Although the snare drum was derived from the tabor during the Renaissance, Europeans appropriated bass drums (davul), cymbals (zil), and other auxiliary percussion from the Ottoman Empire. In particular, Janissary music, a Turkish military style (see youtu.be/D0Fyf63qI_E), profoundly impacted the instrumentation of Western European military music. Use of these instruments spread to military bands and orchestras throughout Europe (Montagu, 2002).

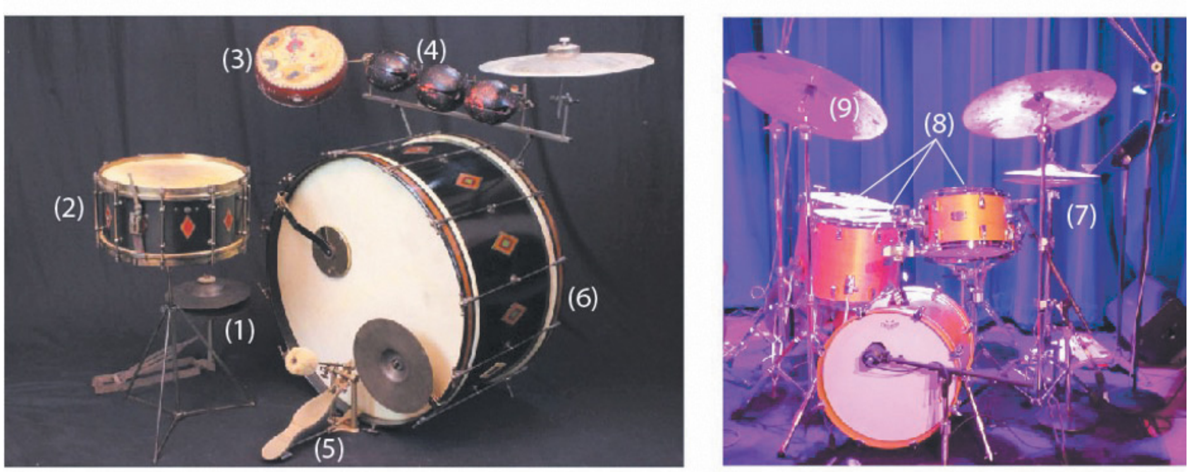
Percussion instruments, specifically drums, played a critical role in many African cultures. Drums were used to communicate between villages, using different tones to broadcast a message to an individual or the entire community. Subsequently, during legalized slavery, drumming was prohibited in the United States. Slave holders could not permit this mode of communication because they did not want enslaved persons to have a form of communication unbeknownst to their enslavers (Dean, 2012). Additionally, stripping Africans of their cultural attachments was a form of psychological warfare to make them more compliant.

However, Congo Square in New Orleans, Louisiana, was one of the few locations where the enslaved could play their native instruments. On days off, enslaved people from the region gathered in Congo Square, now known as Louis Armstrong Park, to worship and celebrate. These practices gave them a meager sense of connection to their cultural heritage. West African rhythms blended with the diverse cultures of New Orleans, setting the stage for many musical genres to be born in the United States, including the blues, jazz, rhythm and blues, and rock and roll.

After the American Civil War, military musicians pawned their instruments and even left instruments on the battlefield, allowing affordable access to instruments to freed slaves and the lower class. The United States was also inundated with immigrants from all over Europe and Asia. Immigrants brought families, cherished items, and, most importantly, musical traditions and indigenous instruments. Consequently, melodies, harmonies, and instruments converged, providing a platform for the auxiliary percussion, toms, and Chinese cymbals (see **Figure 4** for examples of toms and cymbals).

The last salient element is improvisation. Ethnomusicologist Paul Berliner (1994, p. 221) defines improvisation best as the "real-time composing—instantaneous decision making in applying and altering musical materials and conceiving new ideas." The notion of instantaneous composing, individually or collectively, is intertwined in West African cultures. Drums would interact, or employ "call and response," with dancers in sacred ceremonies and secular celebrations (Dean, 2012). This spontaneous exchange of ideas prevailed as a prominent American popular music feature in the early twentieth century. The syncretism of African and Middle Eastern

Figure 4. *Examples of drum kit outfits from the early twentieth century drum kit (**left**) and modern drum kit (**right**). Parts of the drum kits are (1) sock cymbal; (2) snare drum; (3) Chinese tom-tom; (4) wood blocks; (5) bass drum pedal; (6) bass drum; (7) hi-hat; (8) toms; and (9) ride cymbal. Vintage outfit image courtesy of Olympics Drums & Percussion Museum, Portland, Oregon.*



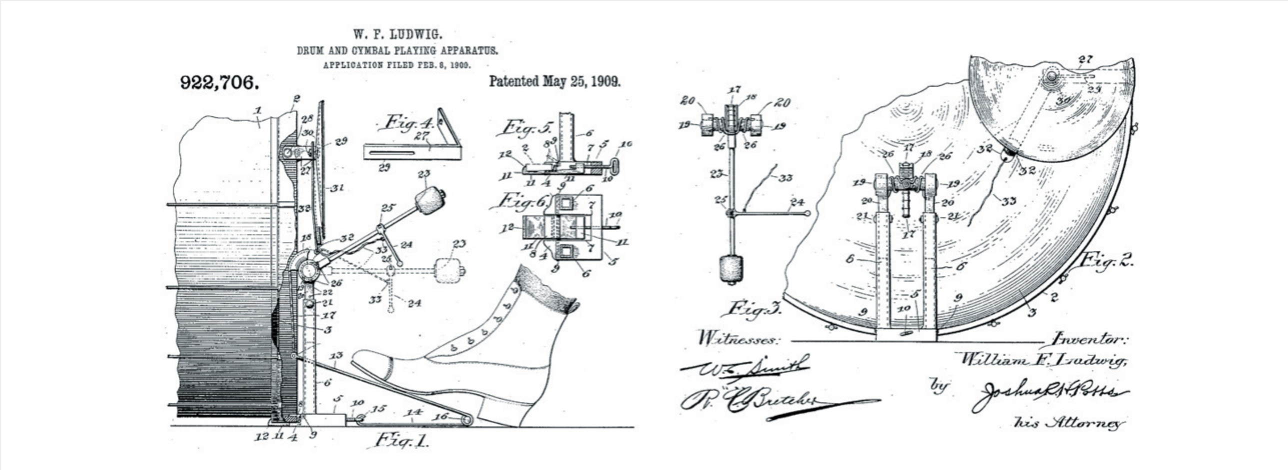


Figure 5. *Ludwig & Ludwig bass drum pedal with variable cymbal playing. From Ludwig (1909).*

Diasporas, elements of immigration in the United States, musical development in Congo Square, and improvisational language set the stage for the development of the modern drum kit.

Drummer Ingenuity

At the end of the nineteenth century, vaudeville and other theatrical variety shows were a significant source of entertainment, especially in the United States and Canada. Percussionists were in such high demand that an individual player needed to play multiple instruments simultaneously, including snare drum, bass drum, cymbal, and other auxiliary percussion. Drummers experimented with placing the snare drum on a chair to be able to also strike the bass drum and cymbals. This new technique was known as double drumming (see youtu.be/qM869WYpp-0?t=131). Drummers also performed as Foley artists by providing an extensive library of sounds and effects for silent films. Contraptions, such as the Chinese tom (tánggu) and woodblock, were attached and surrounded the percussionists to construct sound effects (see **Figure 4**). Drummers enveloping themselves with contraptions eventually led to the hybrid drum set being named a "trap" kit.

As improvisational use of the snare drum increased, companies noticed a need for drummers to be able to play the bass drum without using their hands. To solve this problem, entrepreneurs designed bass drum pedals that were initially cumbersome to use. Initial designs used a pendulum motion to control the pedal with the foot. This was unwieldy, especially for fast tempos. A major innovation was introduced by the Ludwig & Ludwig Drum Company, resulting in the modern bass drum pedal (Ludwig, 1909). Their design utilized a spring to retract the pedal to its original position for additional strikes (see **Figure 5**). The bass drum pedal additionally had a variable arm to strike a cymbal that was also attached to the bass drum.

Drummers gained more arm independence when cymbal strikes could be made by the left foot using a lowboy cymbal or a sock cymbal. The sock cymbal pedal is similar to the bass drum pedal, except that it allows the percussionist to strike two cymbals together using one foot. This contraption would soon evolve into the hi-hat, as seen in **Figure 4.**

The mythology of the transformation of the sock cymbal to the hi-hat is vague and ambiguous. Nonetheless, one drummer, Papa Jo Jones of the Count Basie Orchestra, realized that he wanted to continuously play the sock cymbal, but it was located at the same level as his feet. Eventually, the sock cymbals were raised to the same height as the snare drum and other contraptions, allowing for the drummer to easily reach the colliding cymbals with drumsticks. More importantly, Jones' innovation completely altered the musical expression of the hi-hat. Jones redirected timekeeping from the bass drum to the hi-hat, emphasizing a swing beat, and resulting in the birth of the drummer's modern jazz vocabulary.

A partnership between big band drummer Gene Krupa (see youtu.be/fyAUKU_ImNg) and the drum company

Slingerland established the movement from the early "contraption" set to the modern drum kit, with a new design for the toms. Initially, the calfskin drumhead was simply tacked onto the drum shell, similar to its Chinese counterpart, the tánggu (see **Figure 4**). By placing lugs on the side of the drum, tension in the drumhead could be adjusted, and tunable toms became a standard for future drum outfits.

Krupa also partnered with cymbal maker Avedis Zildjian to construct a more suitable cymbals, including the crash and splash cymbals. Krupa's simple suggestion of making a thinner cymbal was so profound that it produced the standard for all jazz cymbals. Reducing the thickness of the cymbal lowers the resonance frequencies and gives a more subtle attack, augmenting the articulation and allowing more musical expression.

Gretsch Drums was at the forefront of designing the drum kit and the cymbals in the bebop era, starting in the early 1940s. But one innovation stood above the rest. Drums shells were usually made from solid wood. As a result, environmental effects were always an issue when playing. Gretsch invented a manufacturing style that enabled the drum to be crafted, utilizing plywood; this approach mitigated humidity and temperature effects. Although this construction was developed in the late 1920s, its usage did not gain traction until the growing popularity of Gretsch Drums during the bebop era of the 1940s (Brennan, 2020).

In the 1950s, Marion "Chick" Evans and Remo Belli designed new drumheads from mylar, a plastic material used for aircraft in World War II (Brennan, 2020). Originally, animal hide was used for the membrane, but this would succumb to environmental elements such as humidity and temperature. Consistency between multiple hides was also minimal at best. In contrast, the plastic mylar drumheads minimized the environmental and geometric irregularities. Growth in popularity of the mylar heads led to the standardization of drum shell sizes and the modern jazz drum kit as we know it.

Musical Transformation

By the 1940s, a dichotomy between popular and high art music formed two types of influential styles: rhythm and blues and bebop. Rhythm and blues serviced dancers and continued using the identical drum sizes from the early onset of the drum kit. However, bebop's progressive interactive language required subtle modifications to the kit.

Drummer Kenny Clark (see youtu.be/COxQsRokpqQ) revolutionized how the swing feel was driven within the band by moving the swing beat from the hi-hat, as Papa Jo Jones did, to the top cymbal, which eventually was named the ride cymbal (see **Figure 4**). Clark's innovation also led to stylistic adjustments with the snare and bass drums. Rhythmic interjection between the snare drum and bass drum complimented the melody, leading to the term "comping." The new vocabulary required a smaller bass drum. Up to this point, drum kits in the swing era still used bass drums associated with marching bands (24-26 inches in diameter). Many bebop drummers, including Max Roach and Roy Haynes, downsized to a 20-inch bass drum to accommodate the expanding musicality of the drum kit. Cymbals also grew, up to 24 inches. The increased diameters created a darker tone, departing from the higher pitched auxiliary effects cymbal sound.

By this point in history, the drum kit was fully recognizable in its modern form. Drummers have continued to experiment with drum kit construction, but we now turn our attention to exploring the acoustics of the major drum kit components.

Figure 6. *A snare drum as seen from the bottom or the snare head side. The coiled wires running across the snare head are the snares that give the snare drum its characteristic crisp staccato sound. Also shown on the interior of this drum is a dampener pressed against the batter head of the drum. The dampener reduces an unwanted sound that drummers call an "edge ring" by suppressing the third resonance of the batter head.*

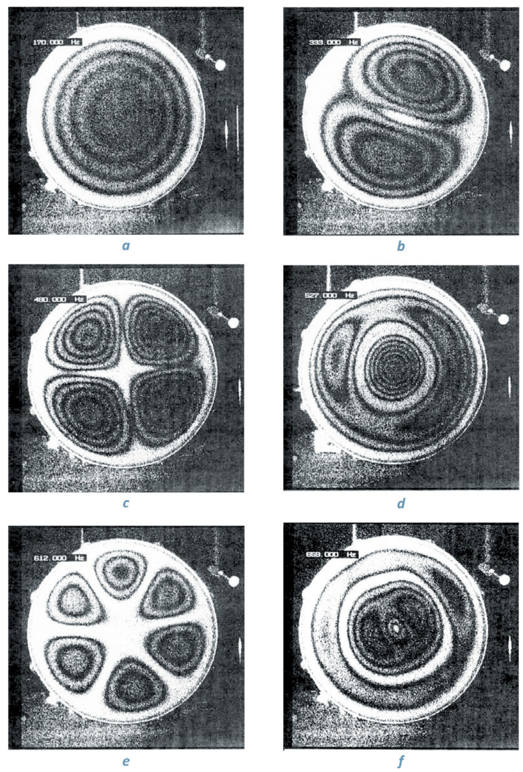


Figure 7. *Holographic interferograms of the first six modes of the batter head of a snare drum (Larkin and Morrison, 2010).* ***a:*** *(0,1) Mode;* ***b:*** *(1,1) mode;* ***c:*** *(2,1) mode;* ***d:*** *(0,2) mode;* ***e:*** *(3,1) mode;* ***f:*** *(1,2) mode. Figures first appeared in Percussive Notes. Reprinted with permission of the Percussive Arts Society, Inc. (see www.pas.org).*

Acoustics of the Snare Drum

The first component of the drum kit we discuss is the acoustics of the snare drum. The snare drum is a cylindrical drum with a drumhead on each side. The top drumhead, or batter head, is the side struck by the drummer. The bottom drumhead, or snare head, has a series of coiled wires, called the snares, stretched across it (see **Figure 6**), which are usually in contact with the snare head. The snares can be placed on or off the drumhead by a lever on the side of the drum (see **Multimedia File 4** at acousticstoday.org/scottmedia) so that when the snares are in contact with the snare head, the drum has the characteristic crisp sound associated with the snare drum (see **Multimedia File 5** at acousticstoday.org/scottmedia).

The modes of vibration of a snare drum as observed through electronic speckle-pattern interferometry are shown in **Figure 7**. In **Figure 6**, an internal dampener that is in contact with the batter head is shown. The dampener suppresses unwanted parts of the snare drum sound. Drummers call the unwanted sound an "edge ring" that does not have the short, staccato-like sound associated with the snare drum (Larkin, 2010). The mode primarily responsible for the edge ring is the (2,1) mode (see **Figure 7c**) The dampener is placed close to an antinode of this mode to reduce the edge ring.

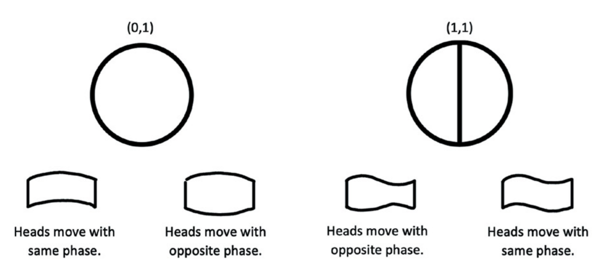
Acoustically, the snare drum differs from the frame drums, timpani, and tabla because the snare drum has two heads that act as a system of coupled oscillators (Rossing et al., 1992). Each drumhead is modeled as a spring-mass system, with the air in-between acting as a coupling spring. Because of the coupling between the heads, there is a mode where the two heads move in phase and a mode where the two heads move in opposite phases (see **Figure 8**). The coupling is particularly strong for the (0,1) and (1,1) membrane modes, but there is also a weak coupling between the two heads for the (0,2) membrane mode.

Tom Drums

The tom drum is a cylindrical drum with a drumhead on top and bottom and is similar in design to the snare drum. The major difference between the tom drum and the snare drum is that the tom drum does not have metal snares on the bottom head.

Drum kits may be equipped with toms of different sizes. Although it is quite clear that the pitch of a tom drum decreases as the size increases, generally we would not expect to be able to associate a particular musical

Figure 8. *Coupled modes of vibration for the batter and snare heads on a snare drum. The strongest coupling is between the (0,1) and (1,1) modes. Figure adapted from Rossing et al. (1992).*



pitch with the sound of the tom drum because the resonances of the drum are not expected to have a harmonic relationship.

Surprisingly, through careful tuning of the batter and resonant (bottom) heads, the frequency ratios of the first three modes of the tom can be aligned to a nearly 1:1.5:2 relationship (Richardson et al., 2012), the same ratio as what gave the timpani its definite pitch! Achieving this tuning relies on the strong coupling between the (0,1) modes of the two heads. No matter how each head is tuned, the (0,1) frequency of each head matches the other head's (0,1) frequency. This allows tuning of other resonances to find a harmonic relationship.

Bass Drum

The kick drum, or bass drum, is the largest cylindrical drum with two heads used in the drum kit. The term "kick" comes from the pedal mechanism. Research done on the bass drum has been mainly focused on the concert or orchestral bass drum (Fletcher and Bassett, 1978). The size of the kick drum is, on average, smaller than a concert bass drum (16-28 inches in diameter for kick drums versus 28-40 inches in diameter for concert bass drums). We can assume that in general the acoustics of the concert bass drum will be largely the same as for a kick drum.

Unlike the timpani, the kick drum is typically struck closer to the center of the drumhead. Playing the timpani in the center of the drumhead results in a dull, thumping sound that is considered undesirable for that instrument, whereas the kick drum is intended to have such a tone.

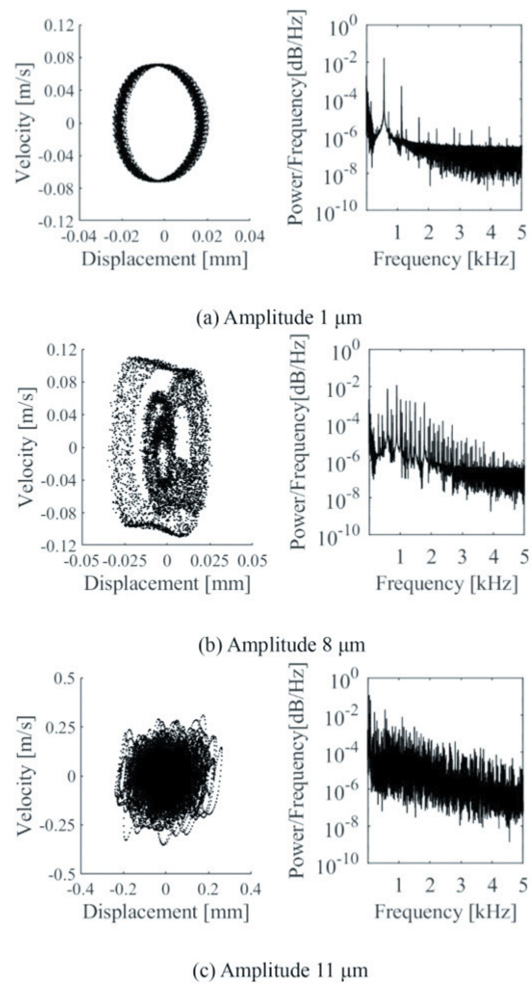


Figure 9. *Phase space plots and sound spectra for cymbal driven sinusoidally with increasing drive amplitudes.* ***a:*** *1 μm;* ***b:*** *8 μm;* ***c:*** *11 μm. Reproduced from Aihara and Ito (2022), with permission of Elsevier.*

Cymbals

Of all the instruments in the drum kit, the cymbals are by far the most acoustically complex. The cymbal is a metallic disc having a slight taper from the edge toward the middle, with a raised dome in the center of the cymbal. The cymbal is mounted on a stand through a hole in the center.

Comparing the normal modes of a cymbal with a flat plate fixed in its center, it is somewhat surprising to find that the mode shapes are similar (Rossing, 2000). That is, the features of the cymbal's profile do not significantly change the shapes of the resonances. Looking at the normal modes of the cymbal does not completely explain its sound because the vibration of the cymbal is highly nonlinear.

Due to their nonlinear behavior, driving a cymbal sinusoidally produces undertones and overtones at extremely low amplitudes (Chaigne et al., 2005), and at high-driving amplitudes, the cymbal vibrations are chaotic. A common way to represent the vibration transitions from quasi-linear to chaotic is by showing a phase space plot in combination with a spectrum. See **Figure 9** for an example from Aihara and Ito (2022).

As a result of the nonlinear nature of its vibration, the spectrum of a crash cymbal changes dramatically after the initial strike. Rossing (2000) described the change in the sound spectrum after the strike on a medium crash cymbal. The sound energy immediately after the strike is dominated by low frequencies, under 700 Hz. The energy shifts to midfrequencies (700-1,000 Hz) and then to the 3- to 5-kHz range within 100 milliseconds after the strike (Rossing, 2000). The high frequencies give the crash cymbal its characteristic "shimmering" sound.

Conclusion

The modern drum kit is composed of instruments with a rich history accessible for acoustical study. We have only touched on a few of the most prominent percussion instruments. Other percussion instruments such as the xylophone, the marimba, chimes, bells, the steelpan family, and auxiliary percussion instruments (such as triangles, tambourines, blocks, and gongs) are all acoustically unique.

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Immersive Wave Experimentation and *The Matrix*

Dirk-Jan van Manen and Johan O. A. Robertsson

In the 1999 blockbuster motion picture *The Matrix* (see imdb.com/title/tt0133093), in perhaps one of the most memorable exchanges in recent movie history, Morpheus, played by American actor Laurence Fishburne, tells Neo, played by Canadian actor Keanu Reeves, "Unfortunately, no one can be told what The Matrix is. You'll have to see it for yourself."

As Neo and the viewers soon learn, The Matrix turns out to be an elaborate simulation, generated by extremely powerful and sentient computers, that acts as a virtual reality for all the senses and constantly tricks the human mind and body into believing that everything it is seeing, hearing, touching, tasting, and smelling is real. Designed to keep humans enslaved mentally and physically, while exploiting them as batteries, Neo could therefore not be told what The Matrix is because the illusory reality created and maintained by it was so compelling that it could no longer be distinguished from reality itself by anyone trapped inside.

Now, scientists from the Swiss Federal Institute of Technology, Zurich, Switzerland (see ethz.ch/en.html) are making headway on an ambitious and much less nefarious project to build a "Matrix" for acoustic waves. Their goal? To trick acoustic and elastic waves propagating in finite-size laboratories into behaving exactly like they would if they were propagating in much larger, extended media. By doing this, the scientists can study wave physics unimpeded by laboratory boundaries and under fully controlled conditions. To achieve this, the scientists propose lining the boundaries of experimental domains with hundreds of active sources and receivers and using technologies like those applied in noise-canceling headphones to compute and control the wavefield on those boundaries in real time.

The task at hand could hardly be any more daunting; not only do the scientists want to suppress the reflections from the physical boundaries, but they also want to include reflections from user-defined virtual scatterers in the extended medium. Furthermore, they want to make it possible for such virtual reflections to interact with the virtual environment again after interacting with scatterers in the experimental domain, that is, facilitating multiple scattering between real and virtual objects.

The Problem of Scale in Laboratory Wave Propagation Experimentation

To understand the scientists' motivation for trying to construct a Matrix for acoustic waves, it helps to know a bit more about laboratory wave experimentation and seismology. Earth materials support compressional (P) wave speeds of up to approximately 14 km/s. Granted, this maximum is only reached for P waves at the core-mantle boundary (and at pressures beyond most, if not all, laboratories), but because earthquakes produce waves with periods of several tens to hundreds of seconds, wavelengths in the Earth can easily reach hundreds of kilometers.

This gives rise to a genuine chicken and egg situation. To research wave physics at those low frequencies and long wavelengths, scientists need to do laboratory experimentation. But to do laboratory experimentation, they need to scale down the experiment, often by factors of 10,000 or more. To scale down the experiment, however, they need to know the physics over those four orders (or more) of scale. Clearly, an impossible task!

Such problems would be drastically reduced, however, if scientists had access to a Matrix for acoustic waves. Although they would still need to know the physics of the embedding medium, the ability to truncate the medium without boundary reflections opens the door to truly low-frequency, long-wavelength experiments that could reduce the required scale factors by, for example, two orders of magnitude or more. This would therefore

https://doi.org/10.1121/AT.2022.18.4.40

enable laboratory wave physics experiments at frequencies and wavelengths much closer to the physics that scientists are really interested in.

A Matrix for Numerical Modeling: Immersive Boundary Conditions

To further their ambitious goals, scientists looked toward a numerical modeling method that they had developed previously, called immersive boundary conditions (IBCs). IBCs were initially conceived as nonreflecting boundaries in numerical simulations.

Without special treatment, the (free) edge of any computational domain on which the wave equation (WE) is discretized (e.g., gridded to enable the computations) acts as a reflecting boundary for the simulated waves, essentially trapping the waves on the numerical domain and masking reflections of real interest. Note that simply fixing the edge of the computational domain does nothing to solve the problem because rigid boundaries reflect waves equally (albeit with different polarity). IBCs thus prevent boundary reflections by treating the edge specially during such computations.

Because directly solving discretizations of the WE yields some of the most complete numerical solution methods but also the most computationally expensive, scientists have been looking for ways to make the computational domain as small as possible. Thus, it is a major computational advantage to be able to truncate the computational domain without generating boundary reflections.

However, the interactions of the waves with structures in the larger background medium are still often important. Thus, it would be ideal to be able to truncate the domain without generating reflections *and* retain, through the application of the special boundary conditions, the interactions of the waves with the background medium. IBCs were specifically developed for this purpose. They immerse a truncated modeling domain in a background medium, allowing waves to propagate seamlessly between the truncated domain and the background. They thus enable arbitrary-order scattering interactions (van Manen et al., 2007).

Briefly, IBCs work as follows (see **Figure 1**). To start the computation, a source (**Figure 1,** *black star*) generates "incident waves" (**Figure 1,** *curved arrow*) that are injected onto a truncated numerical domain D_{sct} enclosed by injection

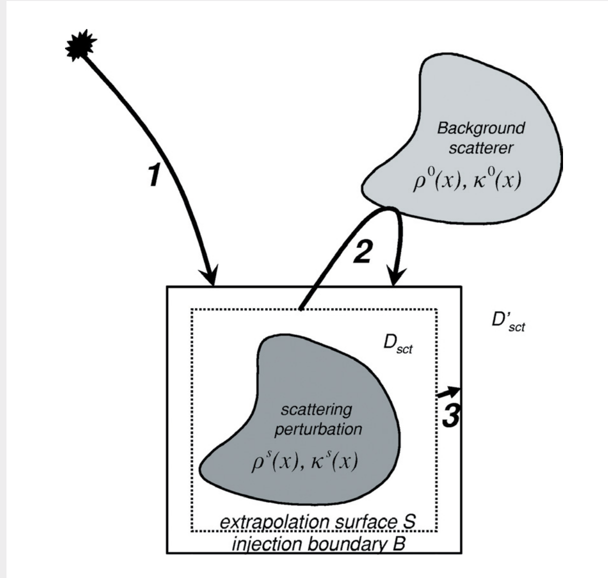


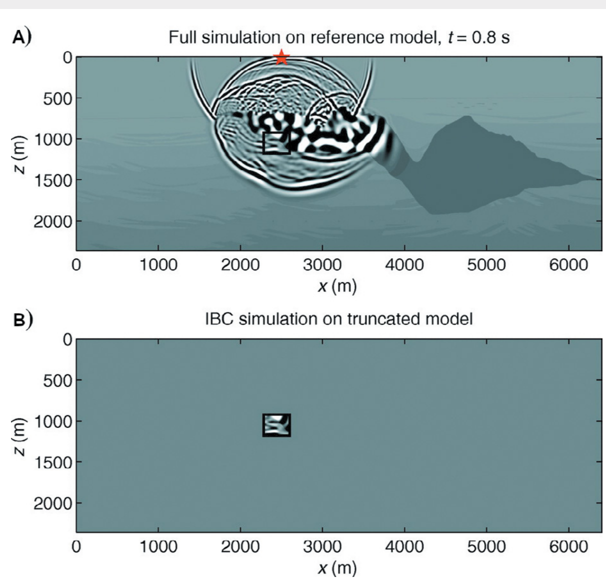
Figure 1. *Immersive boundary conditions (IBCs). At every time step of a numerical simulation, wavefield values recorded a finite distance away from the edge (i.e., on extrapolation surface S) are extrapolated to the edge of the computational domain (i.e., to injection boundary B) as well as through the background model. This allows predicting the outgoing and ingoing waves at the edge very accurately and therefore enables canceling, respectively, injecting those waves.* D_{sc}, *truncated numerical domain;* D'_{sct}, *background model. Reproduced from van Manen et al. (2007), with permission of Acoustical Society of America. Copyright 2007, Acoustical Society of America. See text for details.*

boundary B. At every time step of the simulation, wavefield values observed a finite distance away from the edge, on the extrapolation surface S, are extrapolated to the edge of the computational domain (i.e., to B) and through the background model D'_{sct}. This extrapolation is achieved by convolving (i.e., filtering) the observed wavefield values with a large number of precomputed impulse responses that fully characterize the background model (including, e.g., the "background scatterer"). These impulse responses model both the direct propagation between the extrapolation surface S and the injection boundary B (**Figure 1,** *short arrow*; denoting "extrapolated waves") as well as the interactions with the background medium (**Figure 1,** *curved arrow*; denoting "long-range interactions").

This extrapolation allows predicting the waves that arrive at the boundary very accurately. The predicted outgoing waves are then used to cancel the actual outgoing waves at the edge of the computational domain, like the way anti-sound is used in noise-canceling headphones. The predicted ingoing waves, from the interaction with the larger background model, are instead injected and radiate onto the numerical domain, and this is, in fact, what allows reflections from the background model to be retained.

The extrapolation is done for every time step of the simulation. Similarly, the cancellation and injection take place at every time step. Because the computed ingoing waves radiated back onto the truncated numerical domain can be extrapolated again (and again) after a second (third, fourth, ...) interaction with the scatterers, the method is fully recursive, generating all orders of interactions with the background medium. The resulting wavefields match reference wavefields computed on the full model to within numerical precision. Thus, the scattering on the immersed truncated domain cannot be distinguished from the scattering on the full model, essentially constituting a Matrix for the numerical modeling of acoustic waves.

Figure 2. *IBCs.* ***A:*** *snapshot of a reference simulation computed on a geophysical subsurface model for a source at the surface (****red star****).* ***B:*** *snapshot of a simulation computed on a much smaller part of the same model (i.e.,* ***black square****) but truncated using IBCs. Wavefields computed on the full and the truncated model match each other to within numerical precision. Just from observations of the scattering within the* ***black square****, it is impossible to tell whether the simulation was run on the full or the truncated model. After Broggini et al. (2017), with permission. See text for details.*



An example of an IBC simulation on a severely truncated geophysical model is shown in **Figure 2**. The truncated model is approximately one-hundredth of the size of the full model, indicating that expensive discretizations of the WE on the full model can be almost completely replaced by convolutions (i.e., filtering operations) with precomputed impulse responses in simulations that employ IBCs.

Beyond Numerical Modeling: Immersive Wave Experimentation

A breakthrough came in 2013 with the realization that IBCs can also serve to truncate *physical* wave propagation experiments without boundary reflections and to immerse *physical* experiments in virtual numerical environments in real time (Vasmel et al., 2013). In **Figure 1**, this entails replacing the truncated numerical domain D_{sct} with a *physical* experimentation domain. Furthermore, the extrapolation surface S and the injection boundary B now need physical implementations. These are needed both to measure and cancel, respectively, the physical outgoing waves and to inject and radiate, respectively, the virtual ingoing waves back onto the experimental domain.

With these changes, using IBCs to immerse physical experiments in real time, so-called immersive wave experimentation (IWE), is, in principle, feasible. However, a major challenge still remains, namely the extrapolation of the wavefield values to the boundary of the experimental domain as well as through the numerical environment, including any analog-to-digital and digital-to-analog conversions, must be completed *before* the waves arrive there. That is, the measurement, extrapolation, and control must be *faster* than the waves propagate in the physical experiment. They must be completed faster than the speed of sound!

The requirement for these substantial and real-time computations poses severe latency requirements to any control system implementing such an extrapolation. For example, if the recording surface and the physical boundary are separated by 30 cm and the background medium is water (with a sound speed of 1,500 m/s), then the total system latency cannot exceed 200 μs (i.e., one-fifth of a thousandth of a second). Furthermore, because the wavefield at any point on the recording surface can affect the wavefield at any point on the physical boundary and at any time in the future, the extrapolation constitutes a very computationally intensive task, requiring significant computational resources.

A key enabler for immersive wave experimentation therefore has been a low-latency, acquisition, compute, and control system implementing the IBCs developed in close collaboration with NI (formerly National Instruments) Switzerland. Utilizing so-called field-programmable gate arrays (FPGAs) for the extrapolation computation, the 500-FPGA strong system connects 800 simultaneous inputs to 800 simultaneous outputs through 640,000 individual impulse responses. It does so with a fixed, ultralow system latency of 200 μs, realizing the minimum extrapolation distance of 30 cm for a background medium of water.

Two-Dimensional Immersive Wave Experimentation: Turning a Circular into a Square Domain

Using this ultralow latency system, the first successful two-dimensional (2D) immersive experiments were performed by Becker et al. (2020). This involved immersing a circular physical domain with rigid boundaries into a slightly larger virtual square numerical domain in real time. For arbitrary sound sources in the circular physical experiment, the resulting wavefields, including the tails of multiple-scattered energy in the recordings (i.e., the coda) were virtually indistinguishable from corresponding reference fields modeled for the square domain directly (see **Figure 3**).

Figure 3, A and **B,** shows *experimentally* measured wavefield values (in mV) without and with, respectively, active IBCs recorded in the *circular* physical domain bounded by rigid boundaries. **Figure 3, C** and **D**, shows *numerically* modeled wavefield values (in mV), modeled for the *circular* physical domain and for the slightly larger *square* domain, respectively, bounded by rigid boundaries. **Figure 3, C** and **D**, serves as references for the results in **Figure 3, A** and **B**, respectively. Thus, if the immersion is successful, then the wavefield in **Figure 3B** should look like the wavefield modeled for the square domain in **Figure 3D**, even though it is recorded in the circular physical domain!

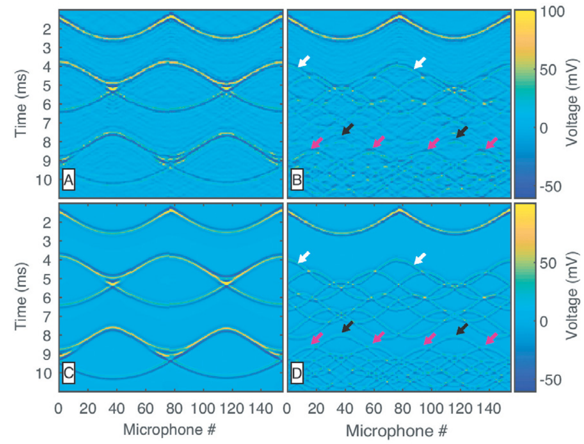


Figure 3. *Two-dimensional (2D) acoustic immersive wave experimentation (IWE). A circular experimentation domain with rigid boundaries is immersed in a slightly larger square numerical domain in real time.* ***A:*** *wavefield recorded in the circular physical domain when the IBC is off.* ***B:*** *wavefield recorded in the circular domain when the IBC is on.* ***C:*** *modeled reference wavefield for the circular domain.* ***D:*** *modeled reference wavefield for the square domain. The close match between the fields in* ***B*** *and* ***D*** *confirms the successful immersion of the circular domain. From Becker (2020), with permission. See text for details.*

Comparing **Figure 3B** with **Figure 3D**, it is clear that the immersed response indeed closely matches the modeled response for the virtual square domain and that the imprint of the underlying circular physical domain has been successfully removed. In **Figure 3, B** and **D,** the *white arrows* denote the first arriving virtual reflection from the bottom boundary of the virtual square domain (introduced onto the physical domain by the IBC). In **Figure 3, B** and **D,** *other arrows* denote waves that have interacted with the virtual domain at least twice, with the *black arrows* denoting the bottom and top and the *pink arrows* denoting the left and right sides. Finally, taking advantage of the fact that the virtual medium can be any desired medium, including a nonphysical one, Becker et al. (2020) showed that it is possible to immerse a (circular) physical domain into a (square) region of nonphysical energy gain materials.

More recently, it has been shown that IBCs can also be used to make objects appear and disappear in real time acoustically. Following up on the theoretical and numerical work by van Manen et al. (2015), Becker et al. (2021)

demonstrated how to cloak a rigid object experimentally for arbitrary, unknown incident wavefields (including for broadband wavefields generated by moving sources).

Next Generation Virtual Acoustics

Encouraged by the successes of 2D IWE, recent studies have started exploring three-dimensional applications of IWE, including on the human scale and in the audible frequency range. Virtual acoustics (VA) is the acoustic counterpart of virtual reality (VR) (see Vorländer, 2020, for an introduction). Compared with existing VA approaches such as wavefield synthesis (Berkhout, 1988; Ahrens, 2012) and higher order ambisonics (Zotter and Frank, 2019), IBC-based VA environments hold out the promise of true, two-way shared acoustic experiences. At least three different types of IBC-based VA environments are envisaged.

Immersed Acoustic Spaces

Here, a single, physical space is equipped with IBCs. The aim is the highest possible realism in terms of placing one or more people and sound sources in that space jointly in a modeled or measured virtual acoustic environment. A number of applications for such immersed acoustic spaces are being considered. One example is use a "show" room where clients can listen to different architectural designs and hear the acoustic impact of using different materials before a building is constructed. Another example are concert halls with reconfigurable acoustic responses.

With IBCs, a simple rectangular room can, in principle, have the perfect response for any type of music. Finally, such spaces could also be used for mobility training of visually impaired people. Some visually impaired people use clicking sounds to navigate acoustically (see bit.ly/3RhpkzY for an example). Immersed acoustic spaces could provide safe, yet acoustically realistic, environments where visually impaired people can learn to navigate.

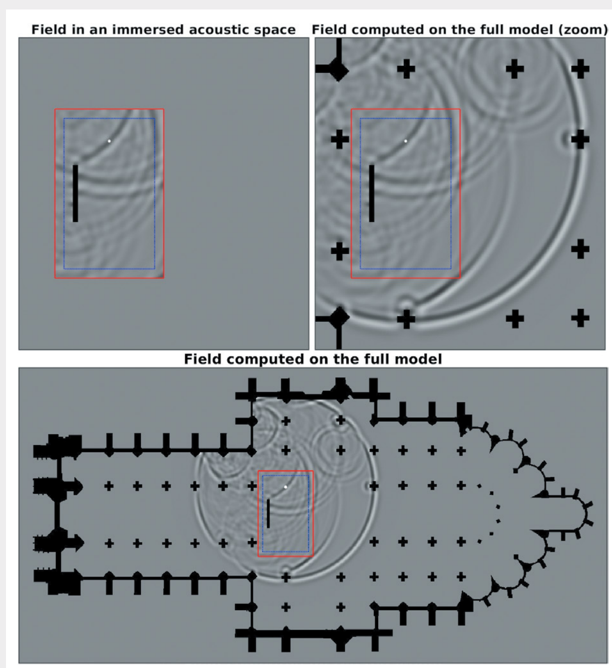
A 2D example of an immersed acoustic space is shown in a top view in **Figure 4**. In this and the following examples, a floor plan of Amiens Cathedral, Amiens, France, has been used to model 2D acoustic impulse responses that completely define the virtual environment.

Figure 4, *top left*, shows a snapshot of a wavefield propagating in a physical space of 3 × 4.5 m while that space is immersed in the larger virtual environment of 28 × 12 m using IBCs. **Figure 4,** *bottom*, shows a snapshot of a wavefield directly computed for the union of the physical and the virtual environments (i.e., the full model) for reference. **Figure 4,** *top right*, shows a zoom in of the reference wavefield. Note the absence of reflections from the rigid walls of the physical space (**Figure 4,** *top left*) because they are canceled by the IBC. Furthermore, it is clear that the field in the immersed space is identical to the reference field, as expected. In **Figure 4,** the *black shapes* denote the real and virtual scatterers (e.g., internal walls and pillars). In **Figure 4,** the *red rectangles* denote the locations of the rigid walls of the physical space and the *blue rectangles* denote the surfaces from which waves are extrapolated.

Shared Acoustic Spaces

Here, two physical spaces with reflecting boundaries are equipped with IBCs, but the IBCs only cover one wall in

Figure 4. *Numerical example of an "immersed acoustic space." **Top left:** a physical space of 3 × 4.5 m (**red rectangle**) is immersed in a virtual space of 28 × 12 m (i.e., a 2D acoustic model of Amiens Cathedral, Amiens, France) using IBCs. Note the absence of boundary reflections in the resulting immersed acoustic space. **Bottom:** reference field directly computed for a full model consisting of the union of the physical and the virtual space. **Top right:** zoom in of the reference field. **Solid black shapes:** scatterers; **white dot:** a (human) source. Acoustic model created from a floor plan by Gothika. See text for details.*



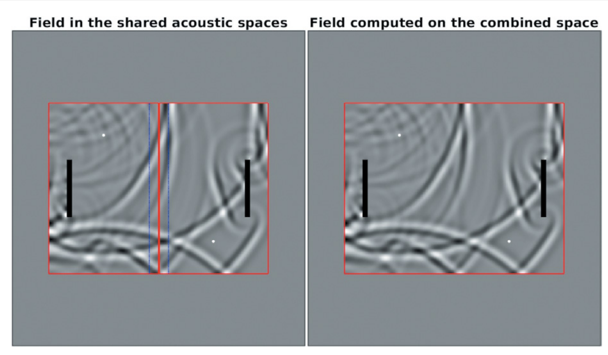


Figure 5. *Numerical example of a "shared acoustic space."* ***Left:*** *a physical space of 3 × 4.5 m (**left red rectangle**) is connected to another physical space of 3 × 4.5 m (**right red rectangle**) using IBCs along the adjacent faces to create a shared acoustic space of 6 × 4.5 m. Note the absence of boundary reflections along the adjacent faces.* ***Right:*** *reference field directly computed for the combined space of 6 × 4.5 m. The union of the fields in the shared acoustic spaces is identical to the reference field.* ***Solid black shapes:*** *scatterers;* ***white dots:*** *a (human) source and receiver;* ***thin blue lines:*** *recording surfaces from which the field is extrapolated. See text for details.*

each space. Furthermore, the impulse responses used in the extrapolation do not contain the acoustic imprint of Amiens Cathedral (or any other virtual medium) but contain only the direct waves required to predict the outgoing waves on the one wall in each space. In this configuration, the focus is *only* on the level of realism achieved in terms of acoustic interactions between people in the different physical spaces and *not* on changing the acoustic characteristics of the physical spaces themselves. Sound propagates correctly between people in the resulting shared space. The resulting room characteristics are the characteristics of the two physical spaces combined. This gives the correct sense of "where people are" and ensures that people know "where to look" in response to acoustic cues (i.e., when complementing sound by matching images).

Example applications of such shared acoustic spaces include virtual meeting rooms and conference venues where a closer interaction and sensory experience between multiple participants in different physical venues are needed. Shared acoustic spaces provide this because they place each participant in the acoustically correct position in the shared space. Another application envisaged are virtual musical performances, bringing remote musicians together acoustically. In this case, the physical rooms used should have reasonable acoustics to begin with because they are not modified but only combined in this configuration.

An example of a shared acoustic space is shown in **Figure 5**. In **Figure 5,** *left*, snapshots of the wavefields propagating in two separate physical spaces of 3 × 4.5 m are shown adjacent to each other while those spaces are acoustically connected to each other using IBCs. The IBCs are only implemented along the right wall of the left physical space and the left wall of the right physical space. Note the absence of reflections from the walls along which the IBCs are implemented. That is, wave fronts intersecting the walls along which the IBCs are implemented are continuous. In **Figure 5,** *right*, a snapshot of the wavefield directly computed for an acoustic space of 6 × 4.5 m (i.e., the size of the combined space) is shown. Once again, the resulting wavefields in the physical spaces match the reference wavefield perfectly.

Shared Immersed Acoustic Spaces

Here, the focus is both on getting the sound to propagate correctly between people in different physical spaces and on immersing the two (or more) physical spaces in a single larger virtual environment. This requires IBCs that completely surround the two physical spaces. As a result, the existing room characteristics of the two spaces are completely suppressed in favor of bringing the two parties together in one larger virtual acoustic environment (i.e., Amiens Cathedral in these examples). This is the most technologically advanced as well as the costliest setup. Example applications of shared immersed acoustic spaces include virtual recording studios for music professionals and concert halls spanning multiple physical venues.

Shared immersed acoustic spaces are illustrated in **Figure 6**. In **Figure 6,** *top left*, the resulting wavefields in the two immersed physical spaces are shown adjacent to each other. In **Figure 6,** *bottom*, a directly computed reference wavefield is shown. In **Figure 6,** *top right*, a zoom in of the reference wavefield is shown. As can be seen, the wavefields, including all higher order interactions between the physical scatterers (e.g., **Figure 6,** *black shapes*, in the physical spaces) and the virtual scatterers (e.g., **Figure 6,** *black shapes*, in the model of Amiens Cathedral), match perfectly.

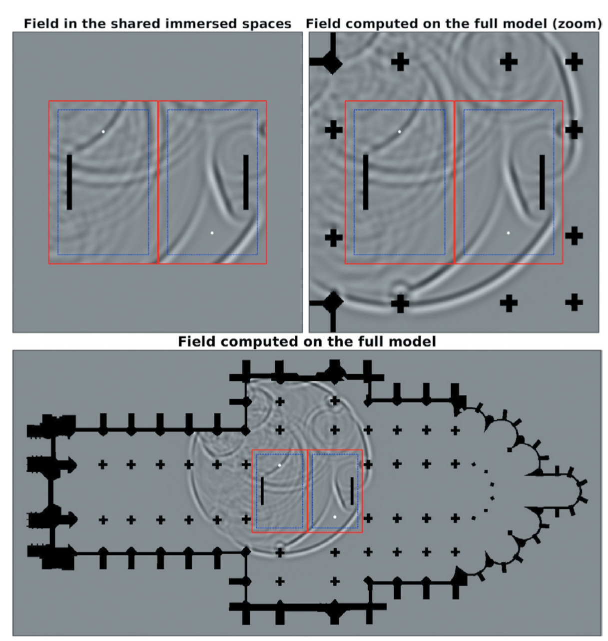


Figure 6. *Numerical example of a "shared immersed acoustic space."* ***Top left:*** *two physical spaces of 3 × 4.5 m (**left** and **right red rectangles**) are simultaneously immersed in a virtual space of 28 × 12 m (i.e., a 2D acoustic model of Amiens Cathedral) using IBCs. Note the absence of boundary reflections in the shared immersed spaces.* ***Bottom:*** *reference field directly computed for the full model consisting of the union of the physical and virtual spaces.* ***Top right:*** *zoom in of the reference field. The field in the shared immersed spaces is identical to the reference field computed for the full model directly. See text for details.*

Can One Hear the Shape of a Room?

In 1966, Polish American mathematician Mark Kac (1966) wrote an article with the now famous title *Can One Hear the Shape of a Drum?* (see also Scott and Morrison, 2022). The frequencies at which a drumhead vibrates depend on its shape. In the article, Kac (1966) asks the question whether the shape can be uniquely determined if the frequencies are known. It took until the early 1990s for three mathematicians, Gordon, Webb, and Wolpert, to show that there indeed exist multiple shapes, nontrivially related to one another, that vibrate with exactly the same frequencies (thus finally answering Kac's question with a clear no) (Gordon et al., 1992).

More recently, Dokmanic et al. (2011), in an article titled *Can One Hear the Shape of a Room: The 2D Polygonal Case*, considered the somewhat related problem of estimating the 2D room geometry from a single acoustic room impulse response (RIR). They discussed the uniqueness of the mapping between the geometry of a planar polygonal room and a single RIR and proposed an algorithm that performs such room shape estimation "blindfolded."

The successful application of 2D acoustic IWE by Becker et al. (2020) by turning a circular wave propagation domain into a square wave propagation domain in real time and the ongoing efforts to apply such technologies to the next generation virtual acoustics force us to reconsider and give new answers to such old questions. Although it may be possible to estimate the shape of the room from a single acoustic RIR, how do we actually know that this RIR was obtained in a physical room with that exact shape and not in a physical room with a different shape that was immersed in another virtual environment using IBCs or IWE? Indeed, when immersing a physical space in a virtual space using IBCs, not just a single RIR but all RIRs are consistent with the virtual space. And thus, even more sophisticated techniques than considered by Dokmanic et al. (2011) that we haven't thought of are all bound to fail. Like Neo, in the famous movie, one would have to find a way to unplug oneself from such a Matrix for acoustic waves to know for sure.

Combining Matrices for Sight and Sound

It is no exaggeration to say that we are at the beginning of another digital transformation of society. The speed and complexity of cost-effective computers, sensors, and connectivity have reached a level that enables immersing individuals in virtual environments and is already being pioneered by companies such as Google and Meta. When exactly we will reach the level of realism portrayed in the movie *The Matrix* is hard to say because the illusion has to work for all the senses (not only sight and hearing but also touch, smell, and taste). The elegant solution by the writers of *The Matrix* was to just bypass the corresponding sensory organs and instead connect the simulation directly to the human information superhighway that is the brain. Although controversial experiments on animals are being carried out by some groups, it will likely still take several decades before humans would be willing to experiment on a large scale with such direct neural connections. Until that time, combining matrices for sight (VR) and sound (VA) seems like an obvious next step. Then touch and, eventually, smell and taste can be added. The question is probably not whether such a combined Matrix can be good enough to fool all humans all the time (as was the goal in the movie) but whether we may soon reach a point where they are good enough that the mind drops its resistance from time to time and we start forgetting, at least temporarily, that what we are experiencing is not "the real thing." Until that time, look out for exciting applications of immersive wave technology in acoustics!

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Reflected Sound: Friend or Foe?

Pavel Zahorik and Matthew T. Neal

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

Reflected Sound Contaminates Acoustical Measurements

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

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

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

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

https://doi.org/10.1121/AT.2022.18.4.48

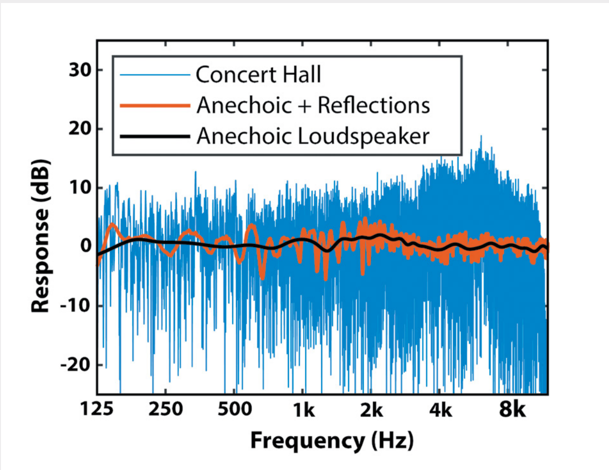


Figure 2. *Frequency responses for a large concert hall (**blue**), the direct sound and a few reflections in the anechoic chamber from **Figure 1** (**orange**), and only the direct sound from the loudspeaker in the anechoic chamber (**black**).*

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

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

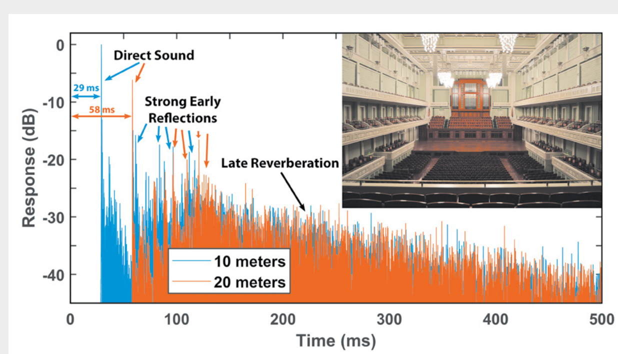
Thus, even within an anechoic chamber, reflections from equipment in the chamber can still cause significant distortions to measurements. These distortions pale in comparison to what a measurement from the same loudspeaker might look like if it is in a reverberant environment, such as a concert hall.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

Reflected Sound is Critical for Good Concert Halls and Sound Quality

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

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

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



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

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

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

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

Reflected Sound and Sound Localization on the Horizontal Plane

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

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

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

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

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

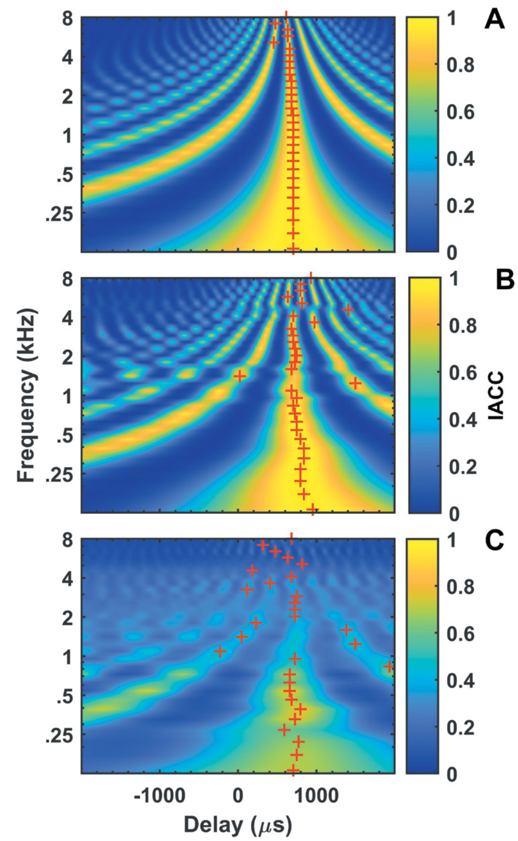


Figure 4. *Binaural cross-correlograms (contour plots of interaural cross-correlation [IACC] as a function of frequency and interaural delay) for an anechoic space (**A**), a simulated room environment with a single reflection (**B**), and a reverberant room environment (**C**). In all cases, the sound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

Reflected Sound Enables Sound Localization in the Vertical Plane

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

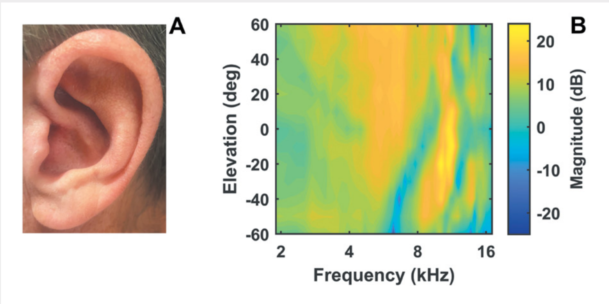


Figure 5. *Left external ear (pinna) of a participant (**A**) and the corresponding head-related transfer functions (HRTFs) as a function of sound source elevation angle (**B**). The sound source azimuth angle was −90°. Note the complex changes in spectral features of the HRTFs as elevation changes.*

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

Reflected Sound, Distance Localization, and Externalization

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

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

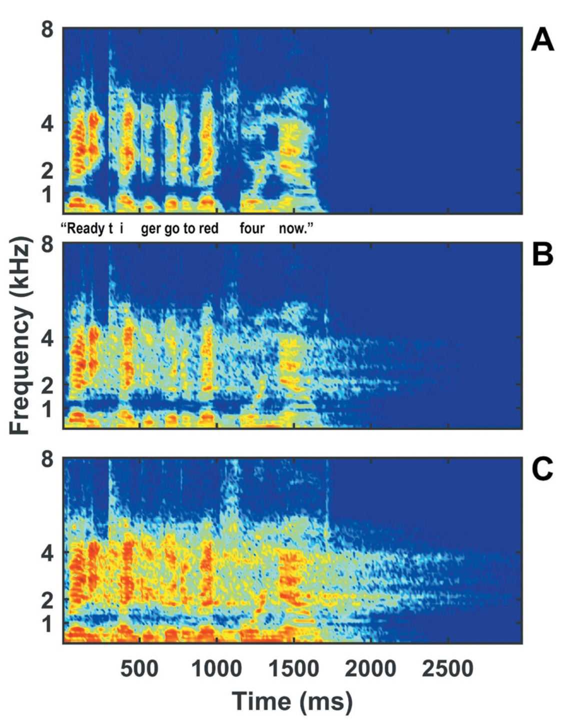
Reverberant sound also has another important perceptual role. It can help support the perception that a source of sound is spatially external to the listener's head. This issue of externalization is critical for sound reproduction over headphones, where in the absence of any additional processing, sound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

Reflected Sound and Speech Understanding

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

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

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



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

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

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

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

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

Reflected Sound in Natural Environments

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

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

Conclusions

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

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Conversation with a Colleague: Robin Glosemeyer Petrone

Robin Glosemeyer Petrone
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Robin Glosemeyer Petrone

Robin Glosemeyer Petrone is the next acoustician in our "Sound Perspectives" essay series "Conversation with a Colleague." Robin received her bachelor's degree from the University of Kansas, Lawrence, and has worked at several acoustics and architecture firms since then. Robin is currently a partner at Threshold Acoustics, Chicago, Illinois. We asked Robin to give us her elevator pitch and then to elaborate on her inspirations, contributions, and hopes for the future.

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

As a partner in Threshold Acoustics (see thresholdacoustics.com), I am hired as an acoustic consultant to advocate for and shape the aural experience in the built environment. Our project types vary greatly, including any spaces where one gathers to learn, share wisdom, and pass along culture, with a specialization in the performing arts.

Most of my time is spent as a translator to decipher descriptions of the human experience of sound. A musician may describe a concert hall as being "clear" or "lush." I pair this description with my scientific knowledge of the behavior of sound, translating the descriptive terms into the application of scientific principles and explaining to an architect how the shape and finishes of the room result in that acoustic perception of clarity or lushness.

We acousticians begin our work in the design process by developing a program for the building. A program is a list of the rooms required to allow a building to function properly. If we are building a concert hall, we require a lobby to hold the guests, restrooms for bio-breaks, a place for the musicians to store their instrument cases and change into their concert attire, and mechanical rooms to provide the building's ventilation, to name a few. We also provide a description of the functions that occur within each room. In the concert hall lobby, the space hosts patrons preshow and during intermission. However, the lobby may also be used as a banquet space for weddings and fundraisers or to host preshow lectures and smaller performances. We describe the basic acoustic conditions required to support each of the functions identified for each space. In a building for music education, for example, we identify the area, or footprint, required for each musician in an orchestral rehearsal room along with the amount of height needed to create the appropriate "acoustic volume" to accommodate the sound energy that each musician produces.

In the design phase, we lay out the building on a site, paying attention to the way people move through the building and to the locational relationship of sound-sensitive spaces to the noise-producing spaces. It is desirable to have the stage and a scene shop next to one another so as to easily move scenery between the two, but the close proximity can also be problematic if the scene shop is being used while there is a production on stage and the sound of hammering can be heard during a performance.

As we move into the detailing of the design, we work with the architects and engineers to shape the way sound is generated in the building and control how it travels from

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a source to a receiver. For instance, we want to help the audience hear a performer on the stage. We educate the architects on how to shape and construct the walls of the theater to provide useful reflecting surfaces that support or add to the direct sound from the performer to the audience members' ears. We do not, however, want the audience to hear the mechanical unit that supplies the air conditioning. In this case, we work with mechanical engineers to design the duct path that delivers the cold air so that it does not deliver the noise of the fan that pushes that air. We also work with the architect to build walls to block the sound radiating out of an air handler.

In the construction phase, the contractors are building from a set of construction drawings and specifications that we developed during design. We meet with the contractors to explain the acoustic goals of the building, and this includes describing the science behind the details that they are asked to construct. We visit the site during construction to review the installation progress, answer questions as contractors implement the design, and watch for conflicts that may prevent the details from being built as intended.

What inspired you to work in this area of scholarship?

My curiosity is boundless. I am also a highly sensitive individual, interpreting all experiences in great detail. My ultimate satisfaction comes from understanding how all of the smallest details function and then come together to create complex systems.

In my youth, I enjoyed the sciences, with physics and mechanics piquing my curiosity. I similarly experienced an intense gravitational pull toward the performing arts. With dance as my primary focus, I also played musical instruments and participated in any theatrical production I could fit into my schedule. Through all my studies and extracurricular activities, I have always experienced a keen sensitivity to our senses and emotions.

In researching universities, I happened on an architectural engineering program at the University of Kansas. Students entered through the School of Architecture to complete architectural studies and design studios while simultaneously completing studies in structural, mechanical, electrical, and lighting systems as well as building contracting in the School of Engineering. In the final years of the program, I chose an emphasis in acoustics that offered a grand intersection, allowing an opportunity to apply scientific knowledge in all aspects of building systems and artistic endeavors through architecture, all in pursuit of the human sensory experience of sound. I supplemented my building acoustics base studies with courses in musical acoustics in the School of Education and in speech and hearing through the Department of Speech-Language-Hearing.

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

In 2020, we opened the Brockman Hall for Opera in the Rice University Shepherd School of Music, Houston, Texas (**Figure 1A**) (see bit.ly/3qixs7z). Working with Allan Greenberg, architect, and Fisher Dachs Associates, theater consultants, my business partner Scott Pfeiffer and I were part of the design team tasked with creating a hall ideally suited to the training of young, exceptionally gifted, aspiring professional opera singers and orchestral musicians and that provides an exquisite balance of the operatic voice with the accompanying orchestra ensemble from the pit.

We began our design process by reviewing more than a hundred opera houses constructed throughout history around the world. We then chose several representative opera houses to investigate in more depth with the client and design team, providing visual imagery of the houses as we described the key layout, shaping, and architectural features that come together to create each opera house's specific acoustics response.

On this project, we were able take our precedent investigations a step further by taking a European tour that allowed the team to see and hear seven opera houses in person. At the conclusion of the tour, the team settled on two favored opera house precedents, one Italianate and one French. We built the two precedent opera houses in a three-dimensional acoustical modeling program. We then introduced sound sources recorded in an anechoic chamber (a room that is devoid of any reflecting surfaces) into the computer models that applied the modeled rooms' acoustic response to create auralizations. Auralizations (Kleiner et al., 1993) are simulated virtual binaural listening experiences rendered at a given position in the computer-modeled space. We brought the team into

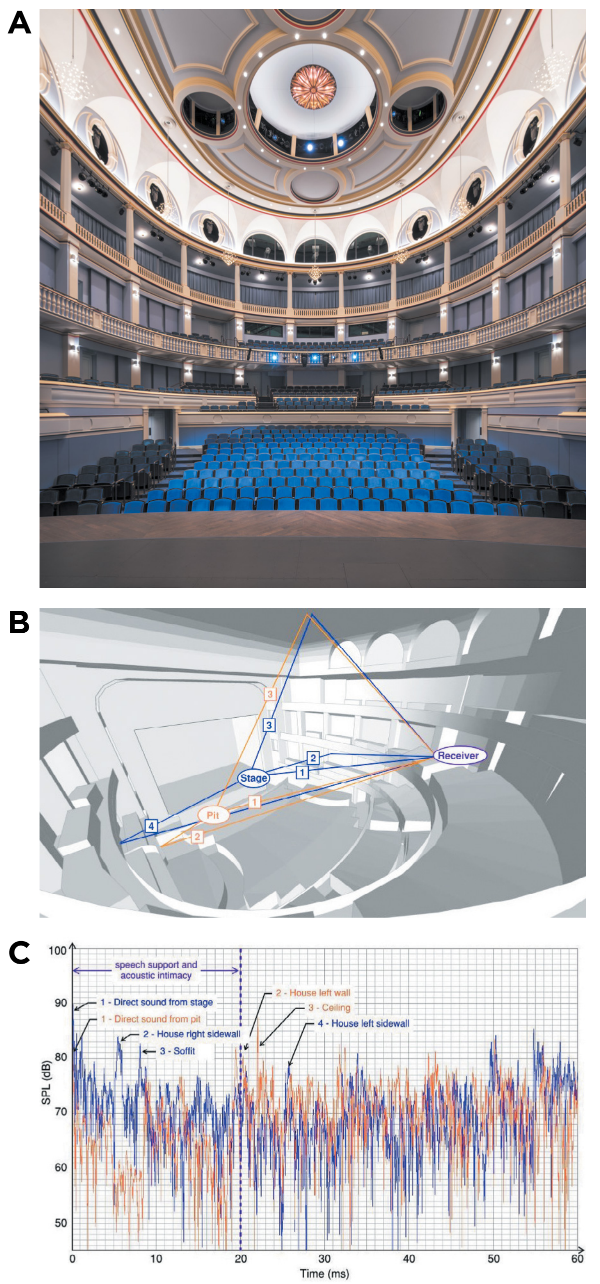

Figure 1. ***A:*** *view from the stage into the audience chamber of the Lucian and Nancy Morrison Theater in the Brockman Hall for Opera, Rice University, Houston, Texas.* ***B:*** *three-dimensional model illustrating the reflection paths from an opera singer on stage (**blue**) and a musician in the pit (**orange**) to an audience member seated in the Grand Tier of the Lucian and Nancy Morrison Theater.* ***C:*** *receiver impulse responses comparing the balance of the sound from a stage and from a pit source as heard by an audience member seated in the Grand Tier of the Lucian and Nancy Morrison Theater. SPL, sound pressure level.*

a space with a 22-channel spatial audio system and a 4-meter diagonal video screen to immerse them visually and aurally in the virtual experience of the opera houses, allowing them to listen to side-by-side comparisons of the precedent houses with the concepts for the new theater at Rice University.

The acoustic design of the 600-seat opera house that emerged from this process envelopes the listener aurally in a room with clear ties to both the French and Italian operatic traditions. It engenders a sense of intimacy and immediacy, providing a strong connection between performer and audience.

The SketchUp model (**Figure 1B**) and the measured impulse responses (**Figure 1C**) illustrate the direct and early-order reflection paths and the balance of sound energy from both a vocal source on the stage (**Figure 1B,** *blue*) and the concert master source in the pit (**Figure 1B,** *orange*) to a receiver seated in the Grand Tier. Direct sound from the stage and pit arrives at the listener's ear within fractions of a millisecond of each other, with a 10 dB preference toward the voice on stage. First-order reflections from the side wall and soffit continue to favor the voice in both energy level and time of arrival, arriving within the critical first 20-millisecond time window that supports speech intelligibility and creates the perception of acoustic intimacy.

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

The main thrust of my work is to share research and project-specific knowledge of sound behavior with clients, design teams, and contractors, showing everyone how their work impacts the spaces we build together. I am driven by the belief in designs where acoustics and audio/video (AV) become a natural extension of a unified design rather than an additive element.

I also take opportunities to share my knowledge through teaching engagements, invited presentations, and publications. I am currently an adjunct lecturer in the School of Communication Master of Sound Arts and Industries Program at Northwestern University, Evanston, Illinois. I have a recurring role as an invited lecturer and advisor for the third-year architecture studios at the Illinois Institute of Technology, Chicago, Illinois.

I continue outreach efforts as an invited speaker focusing on the topics of music and architecture for the Los Angeles Philharmonic Music for Elementary Educators Series, Los Angeles, California, on the exploration of sound in architecture for the Southern California Institute of Architecture, Los Angeles, and bringing midcentury masterpieces back to life at the International Theatre Engineering and Architecture Conference. As the Covid-19 pandemic entered its second year, Scott Pfeiffer and I shared our knowledge with the League of American Orchestras, New York, New York, on the topic *Balancing Acoustics and Physical Distancing as Orchestras Return to Their Halls*.

I am currently chair of the Concert Hall Research Group (CHRG) (see chrgasa.org), a subcommittee of the Acoustical Society of America (ASA) Technical Committee on Architectural Acoustics (TCAA). CHRG's mission is to advance the knowledge and understanding of acoustic design for music performance spaces. I have cherished my roles in co-organizing the 2003, 2014, and 2019 CHRG Summer Institutes. These Summer Camps for Acousticians are week-long conferences held at an outdoor music facility to facilitate the exchange of ideas between practicing acoustic consultants in performing arts, faculty and researchers in architectural acoustics, and college students studying or interested in architectural acoustics, with a goal of furthering research into the subjective preferences of listeners and improving our tools for design and analysis in acoustic modeling and measurement methods.

Through the ASA, I am currently serving my second term as a voting member on the ASA Books Committee, representing the TCAA and am cochair of the Newman Student Award Fund where I maintain the Student Design Competition (see bit.ly/3AGmPA5).

I am a co-author of *Classroom Acoustics: A Resource for Creating Learning Environments with Desirable Listening Conditions* (see bit.ly/3cEBIuM). This ASA booklet is intended to raise awareness of the impact of the aural environment on learning and was created to be a supplemental resource for architects, educators, and school planners. It provides a general overview of classroom acoustics problems and their solutions for both new school construction and renovation.

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

When I was introduced to the world of acoustics by Bob Coffeen in my first architectural acoustics course at university, I thought it kismet to have found a profession where I could bring together a seemingly disparate set of skills and interests into a profession that would allow me to endeavor to improve the human condition. It is energizing to know that with each project I am able to help people: help them more easily communicate and learn; improve their ability to focus; reduce their stress; and facilitate the creation and enjoyment of art that can elevate the human experience.

But there is another awesome, if not necessarily obvious, aspect of working as an acoustician in the building industry I treasure. It is understanding that my job allows me to spread my impact far beyond the projects on which I have the privilege to work. With a project, I have the opportunity to advocate for our aural environments and to share my knowledge with my architect, engineer, and contractor colleagues so that they can learn it for the project at hand and carry that knowledge forward onto the next project.

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New Efforts to Bring Acoustics Standards into the Curriculum

Nancy A. Blair-DeLeon

Ask anyone around you to provide their perspective on a sound. Their answers are as unique as they are individuals. What might be perceived as a sound by one person could arguably be defined as noise by another. Ultimately, it's all about our individual processing of acoustics. Yet how do we facilitate a foundation for the understanding and practical application of sound and acoustics? One answer is through the development and maintenance of an accredited body of standards touching all aspects of the acoustics field.

The fact is that acoustics standards matter because they touch so many components of our common humanity, from underwater acoustics to sound in quiet protected natural and residential areas to classrooms and much more. For example, most people think of a classroom as a learning environment (Brill et al., 2018). A noisy classroom, however, can make hearing and understanding difficult. That noise or those sounds are composed of many factors, from the location of the classroom to outdoor sources.

The Acoustical Society of America and Classroom Acoustics and Health Care

Since mid-1997, the Acoustical Society of America (ASA) has led the way in developing a series of classroom acoustic standards (Nelson et al., 2002). These standards help school planners and architects provide good acoustical criteria, design requirements, and guidelines for learning spaces in which speech communication is an important part of the learning process.

A second key example of an acoustics standard in action is the ASA/American National Standard Institute (ANSI) S12.70, *Criteria for Evaluating Speech Privacy in Healthcare Facilities* (see bit.ly/3Twl6Gr). This standard provides a relationship between speech privacy descriptors and speech privacy expectations for various enclosed and open-plan health-care spaces including treatment rooms, pharmacies, and waiting areas. When visiting a health-care provider, for example, you have the expectation and have become accustomed to confidential discussions between yourself and your provider while in the examination room. What many may not realize is that the often-muffled sounds you hear between exam rooms happens by design. ASA/ANSI S12.70 provides design criteria for achieving acceptable speech privacy.

Acoustical Society of America Standards

ASA Standards help frame the acoustic field's consensus on the study and practical application of sound. They also help identify discourse and provide industry solutions that frame a sustainable world that began in 1930 when the Society formed the ASA Committee on Standards (ASACOS), the organization's primary vehicle for promoting the practical application of acoustics (Blaeser et al., 2006).

ASA Standards also are the link to safety and the preservation and restoration of acoustical environments, harmonizing compatibility among a global network of products. Moreover, an ASA core value states, "Attraction, development, encouragement, education, and mentoring of current and future generations of acousticians from diverse backgrounds (acousticalsociety.org/policy-statements)."

Led by Stephen J. Lind, ASACOS Chair and ASA Standards Director (and an expert in environmental acoustics who worked with Trane Air Conditioning in its La Crosse, Wisconsin, acoustics lab for 21 years), ASA's standards span disciplines represented by 14 ASA Technical Committees. This includes work on both American national standards and international standards in acoustics, mechanical vibration and shock, bioacoustics, animal bioacoustics, and noise.

The Need for Standards

Companies, organizations, and government agencies rely on standardization to meet their goals. By participating in standards development activities, stakeholders streamline

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processes, reduce costs, and maintain market relevance and value. ASA's program exists to help people in various technical competencies align the way they do things in an environment where science and practitioners approach things differently but combined have the potential to create synergy and consensus-driven solutions. "The fact is industry relies on previously standardized technologies and terminologies to allow cross-border interoperability through compliance on products and systems manufactured in one country while sold and used in another," said Stephen Lind.

Ultimately, ASA's mission and continued work connect in a fundamental way to the missions of college and university curricula in acoustics and related fields. The development of industry standards, the cornerstone for the academic curricula of engineers, researchers, and future leaders, lays the groundwork of critical skills required for professional advancement plus a solid understanding of economic and technical impact of shared principles and practices globally.

For instance, postsecondary engineering students learn about quality management systems (QMSs) that lead to International Organization for Standardization (ISO) 9001 certification (see bit.ly/3pN5W1J), a program developed in support of ISO 9001, an international standard for creating QMSs published by the ISO. ISO 9001 is critical because it sets out the requirements for a QMS to help organizations be more efficient and improve overall customer satisfaction.

As a part of the ASA acoustics standards process, every standard has requirements to develop uncertainty allowances to aid in the validation and verification of acoustic measurements. When considering whether a product is contributing noise to the work environment, the engineer or acoustic technician making the measurements must know if the measurements are within specifications. In the acoustics realm, those measurements all start with a microphone and a calibrator.

To this end, faculty and practitioners need to be aware of acoustic standards that apply to their measurements (e.g., jet noise measurements, underwater ship noise, audiometric assessments) and then be capable of using that guidance correctly. Academic programs that teach students about the role standards play and incorporate them into curriculum will ultimately be preparing students for work in the real world where standards are viewed as lynchpins for safety, improvement of the human condition, and the preservation and restoration of acoustical environments.

Standards Education

ASA Standards believes education and advanced training of the next generation of standardization professionals are also vital for the United States to remain competitive in global markets. The first step in this endeavor is educating the acoustics community about the importance of standardization, including the application of the standards. At the same time, receiving postgraduate professional development training and certifications are equally valuable. When combined, they provide an understanding plus the "how" and "why" around implementation and adherence to the best practices in the field.

"I've learned about standards by working with professional colleagues who have been proactive in standards development," says Donald Peterson at Northern Illinois University, DeKalb (see bit.ly/3wK2XLh) and chair of ASA Standards Working Groups 39 S2 and S3, Human Exposure to Mechanical Vibration and Shock. "Standards didn't really exist in my undergraduate or graduate education in the classroom and lab. And that's the biggest challenge. If we look at faculty today, they're not likely going to use standards unless it's something they're already comfortable with, which is not common because many of them may not have had much to do with standards. They may not have developed a solid standards background from their own educational experiences."

A recent survey conducted by The American Society of Mechanical Engineers (ASME) project, Vision 2030, concluded that "almost 50% of early career engineers lack standards knowledge (see bit.ly/3CA0mXW)." Still, technical standards are used to establish consistent engineering or technical criteria, methodologies, processes, and best practices. The challenge is that standards are referred to but have not necessarily been a part of educational learning systems for several reasons including: lack of access and limited budgets or because the faculty may not necessarily be savvy when it comes to international and national standards application; that is, they are educators whose roles are different from those in the field who are applying such standards.

With more exposure to and training in the use of acoustical standards, undergraduate and graduate students likely would be able to accelerate their preparation in launching their professional careers. "As it stands now, a young engineer starting out in a job will typically focus on a handful of standards most pertinent to their industry role," says Derrick Knight, acoustic engineer with Trane Technologies and vice chair of Working Group S12, Noise. "As their expertise deepens, they will typically begin to wonder why certain parts of the standard are written the way that they are. They will develop opinions about how the standard might be clarified or improved to reflect new techniques, materials, or equipment. At this point, the engineer is ready to contribute to standards development where they can discuss the smallest details and biggest ideas with other professionals in their field to make improvements."

Increased discussions and partnerships have begun to emerge within colleges, universities, and professional societies as well as discussions with the Accreditation Board for Engineering and Technology (ABET), all of which understand the value in including standards as an integral part of the learning continuum. Most recently, ASTM International was among the sponsors of the 2022 Capstone Design Conference (see bit.ly/3CQfwsa), which took place June 6-8, 2022, at the University of Texas at Dallas. This conference provided a forum for faculty, staff, students, and industry representatives to share ideas about improving and/or starting engineering capstone design courses.

In addition, the ANSI education programs and resources continue to bring awareness to the importance of standards and conformity assessment to academia, students, and the public. Through their initiatives, ANSI has been successful at bringing together expertise from across the standards community, and through these initiatives has also supported implementation of the education-related aspects of the United States Standards Strategy (USSS), a guide on how the United States develops standards and participates in the international standards-setting process (see bit.ly/3e8sqaU).

Strategic Framework

All told, ASA Standards has spent the last two years examining its standards development program from business models to organizational membership, dues structure, benefits, and membership recruitment to leverage the growing need for acoustics standards with ever-evolving technologies and methods in the marketplace. Since then, and with the support of volunteers, ASA Standards has placed an emphasis on the value and reach of the ASA brand from launching a new website (see asastandards.org) and a standards storefront (see bit.ly/3RmTEJ0) to greater conference visibility and brand outreach through social media platforms. With the combined efforts of volunteers, organizational members, educators, technical experts, and governance and as the result of rigorous discussions during the May 2022 ASA Standards meetings held in conjunction with the 182nd meeting of the ASA (see bit.ly/3B7ShJf), ASA Standards is excited to develop a framework for providing resources and developing partnerships aimed at exceeding educational and vocational objectives that reinforce knowledge and skills as university students and practitioners progress through their educational aspirations.

"Our goals at ASA Standards are to create new partnerships with educational institutions, national standards bodies, and other professional organizations to add value in supporting education of new generations of acousticians," said Stephen Lind.

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The Bureau of Ocean Energy Management and Ocean Noise

Shane Guan, Jill Lewandowski, and Erica Staaterman

Introduction

In recent years, underwater anthropogenic sound impacts on marine life has become a well-recognized environmental issue among scientists, conservationists, regulators, and the general public. Many of these sounds could adversely affect marine life and fisheries (Erbe et al., 2018; Popper and Hawkins, 2019).

The US Bureau of Ocean Energy Management (BOEM; see www.boem.gov) and its predecessor agencies have a mission to manage the development of US Outer Continental Shelf (OCS) energy and mineral resources in an environmentally and economically responsible way. Thus, BOEM has been a pioneer in studying and mitigating the environmental effects of anthropogenic sound generated by the industrial activities that it regulates.

Founded in 1973, BOEM's Environmental Studies Program (ESP: see www.boem.gov/environmental-studies) helps to assess and understand how the Bureau's decision making impacts the environment. As such, it was the first US government entity to conduct studies on industrial noise impacts on marine life and provide the regulatory framework to monitor and mitigate such impacts. Today, the ESP is still one of the leading US government funders supporting scientific research in this field. Over the past three decades, BOEM has invested over $95 million on studies related to protected species and underwater noise through four general research themes: (1) empirical laboratory and field studies; (2) literature reviews, syntheses, and workshops; (3) sound source verification and modeling; and (4) impact monitoring.

To strengthen its role as a driving force within the regulatory community on sound in the marine environment, BOEM established the Center for Marine Acoustics (CMA: see www.boem.gov/center-marine-acoustics) in 2020 to integrate the Bureau's acoustic-related science and policy work. The functions of the CMA are to (1) build models that address current needs and drive improvements in the field; (2) track emerging science, fill data gaps, and apply new risk assessment methods; (3) address key policy and management improvements, both internal and external; (4) improve stakeholder understanding of actual risks; and (5) develop relationships with domestic and international organizations to advance shared goals. Staffed by acoustic-modeling experts and bioacousticians, the CMA is positioned to take the lead in assessing and addressing anthropogenic sound and its environmental impacts within the US federal government and internationally.

Early Research: Pioneer Studies on Noise Impacts from Oil and Gas Activities

In the 1980s, BOEM was the first US government agency to support and fund research that investigated industrial noise impacts on marine mammals. Most of these studies conducted aerial or vessel observations to document the behavioral responses and distributions of migrating or feeding mysticetes (i.e., baleen whales) and pinnipeds (i.e., seals and sea lions) when exposed to underwater noise from offshore oil and gas exploration and development. Anthropogenic sound sources examined included airguns for marine seismic surveys, drilling for oil and gas extraction and production, dredging and pile driving for industrial facility construction, and various vessels including icebreakers.

These pioneer studies established a conceptual acoustic source-path-receiver model that became widely used to assess the potential effects of anthropogenic noise on marine mammals based on various distances from the source. Following these initial studies, BOEM funded additional research on sperm and humpback whales' behavioral response to seismic airgun exposures in the Gulf of Mexico (2002–2005) and Australia (2011–2017), respectively.

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Current Research: Comprehensive Studies on Ocean Noise and Impacts

Studies on Anthropogenic Sound Sources and Sound Propagation

Over the past decade or so, the United States has begun to develop offshore renewable energy in the OCS, and BOEM has invested heavily toward understanding underwater sounds from the construction and operations of offshore wind facilities.

One of the most notable studies is the Realtime Opportunity for Development Environmental Observations (RODEO: see www.boem.gov/rodeo), led by Dr. James Miller of the University of Rhode Island, Kingston, in collaboration with the Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts, and Marine Acoustics, Inc., Middletown, Rhode Island. Acoustics research under RODEO included investigation of sound field characteristics of impact pile driving on large wind turbine installation. Both acoustic pressure and particle motion data were collected in the water column at various distances using mobile and stationary acoustic sensors. Studies also investigated sound levels and frequency contents from pile driving with and without air bubble curtains. After completing RODEO, BOEM initiated RODEO II to collect data on substrate-borne vibration, analyze interpulse sound intervals, and measure the impulsiveness of pile-driving sound as a function of distance.

Additionally, BOEM funded a study to develop a methodology for computing the received sound field as a function of range, bearing, and depth from nonpoint sources, such as impact pile driving in a range-dependent environment. The method incorporates the newly established damped cylindrical spreading model, which includes sediment type and bathymetry information. The study created an Excel spreadsheet-based acoustic prediction tool (see www.boem.gov/environment/dcs-v3) to allow regulators to predict more accurate and robust acoustic impact zones for wind farm construction-related impact pile driving.

Studies on Animal Psychoacoustics and Effects of Sound on Marine Life

BOEM has also undertaken several cutting-edge research to understand auditory perception and behavioral responses of animals when exposed to underwater sound. One of the critical information gaps in assessing marine mammal noise effects is the lack of sufficient understanding of low-frequency cetacean (i.e., baleen whales) auditory capabilities and sensitivities. To address this data gap, BOEM is jointly funding two studies with the Office of Naval Research, the Marine Mammal Commission (MMC), and National Oceanic and Atmospheric Administration (NOAA). These studies will collect auditory evoked potential hearing thresholds from temporarily restrained minke whales (led by Dr. Dorian Houser of the National Marine Mammal Foundation) and investigate bone conduction in baleen whales using finite-element modeling (led by Dr. Ted Cranford of San Diego State University [SDSU], San Diego, California).

Until recently, relatively few studies had been performed to establish audiograms and examine noise effects in marine reptiles, fishes, and invertebrates. To address this information need, BOEM has funded research investigating hearing sensitivity in leatherback sea turtles and behavioral responses of black sea bass and longfin squid exposed to pile-driving sound pressure and particle motion. In the latter study, BOEM sponsored Dr. Aran Mooney at WHOI to conduct lab-based and field experiments before, during, and after exposure to pile-driving playback sounds in a tank and in situ pile driving in a mesocosm.

In 2014, BOEM helped fund a panel led by Dr. Arthur N. Popper and Dr. Richard R. Fay to develop a set of criteria for fish and sea turtle noise exposure. The outcome was the publication of the Acoustical Society of America (ASA) S3/SC1 Standards titled *Sound Exposure Guidelines for Fishes and Sea Turtles*, registered with the American National Standards Institute (Popper et al., 2014).

Studies on Acoustic Habitat

The acoustic environment is one of the essential ecological elements for marine animals that are primarily acoustically oriented. The soundscape within the aquatic environment is filled with sound from geophysical sources, biological sources, and anthropogenic sources. A good understanding of the temporal, spatial, and spectral dynamics of these sound sources is critical for BOEM to plan its OCS activities and assess potential impacts. Through the National Oceanographic Partnership Program, BOEM co-funded Dr. Jennifer Miksis-Olds of the University of New Hampshire, Durham, to establish the

Atlantic Deepwater Ecosystem Observatory Network (ADEON; see adeon.unh.edu) to collect and analyze large soundscape datasets across the deepwater regions of the Atlantic OCS. The baseline data collected from ADEON are being used for BOEM to assess its Atlantic OCS energy and minerals activities in the region.

Underwater Noise Monitoring, Mitigation, and Risk Assessment

In addition to conducting underwater noise- and impact-related research, BOEM contributes a large portion of its efforts toward monitoring and mitigating underwater noise from its regulated OCS activities. For example, for over 10 years, BOEM has collaborated with NOAA's Marine Mammal Laboratory to conduct passive acoustic monitoring (PAM) during offshore oil and gas development for impact monitoring in the Arctic (see bit.ly/3Td0FxA).

BOEM is currently working with stakeholders through the Regional Wildlife Science Collaborative (see rwsc.org) to develop a regional PAM network in the Atlantic to monitor for the presence of marine mammals in relation to offshore wind development. Additionally, BOEM has supported the improvement of PAMGuard, a widely used open-source software developed by Dr. Douglas Gillespie of the University of Saint Andrews, Saint Andrews, Scotland, United Kingdom, as well as the Tethys metadata system developed by Dr. Marie Roch of SDSU for analyzing and organizing marine mammal detections from PAM.

Although behavioral responses and auditory impairments from noise exposure provide certain benchmarks to gauge the effects on individual animals, these parameters often cannot assess the population-level effects to predict the significance of biological impacts. Under the auspices of the National Academies of Sciences, a scientific committee was formed to propose a conceptual model of Population Consequences of Disturbance (PCoD). In 2015, BOEM funded a study to review ways to quantify exposure-related changes in marine mammal behavior, health, or body condition of individual from multiple stressors, including loss of habitat, pollution, anthropogenic noise, and fisheries bycatch, and to make recommendations for future research initiatives.

However, implementation of a PCoD model for regulatory process is not straightforward due to the lack of specific and detailed data required to carry out the analyses. In 2019, BOEM convened a group of experts led by Dr. Brandon Southall to create an analytical risk assessment framework that specifically focuses on geological and geophysical surveys in the Gulf of Mexico. This novel framework incorporates key information about a population's status, the behavioral context in which it encounters sound sources, and the spectral overlap between the sound source and the species' hearing capabilities. This framework is currently being applied to evaluate the risks of staggered versus simultaneous construction of several offshore wind farms in the New England area.

Working with Partners and Looking Forward

BOEM's work on acoustics as well as on a host of other physical, biological, and sociological issues is wholly dependent on partnerships. BOEM is a small agency with just under 600 full-time employees and limited research funding, so we rely heavily on partners, both domestic and international, to achieve our mission goals. Whenever possible, BOEM seeks partnerships to maximize the utility of results and extend limited budgets by leveraging funds with other interested federal, state, and private stakeholders. We conduct many of our studies through collaboration and cost sharing with other organizations, such as the Navy, Department of Energy, NOAA, MMC, and the Joint Industry Programme on Sound and Marine Life (JIP).

Because the United States strives to reduce its reliance on fossil fuels, BOEM is increasingly involved in the development of offshore renewable energy. At the same time, BOEM's environmental long-term vision of elevating the ESP to become "First in Class" is actively pushing the boundary to understand ocean noise and its effects on marine life. Some of the cutting edge/pioneer studies we are developing include looking into substrate-borne vibroacoustic disturbances from offshore renewable energy structure construction and operations and their potential effects to the benthic ecosystem; investigating marine mammal noise-induced hearing threshold shifts from exposure to complex noise (noise that includes both impulsive and nonimpulsive components); and developing synergetic models to assess cumulative effects from multiple stressors. Additionally, BOEM is working on developing a multiyear national acoustic science strategy to prioritize research and assessments needs to support BOEM's mission.

BOEM is also exploring ways to incentivize the use of noise abatement methods that reduce the levels of noise that are introduced into the marine environment, which could serve as a primary mitigation approach. For example, in 2013, BOEM hosted the Quieting Technologies workshop with acoustics experts to investigate technologies that could reduce underwater noise from marine seismic surveys, pile driving, and associated vessel activities. Since then, BOEM has worked with the JIP on Marine Vibroseis to support development of alternatives to airguns and is currently working with other federal agencies to establish performance targets and incentives for noise reduction during wind farm construction.

Finally, BOEM recognizes the interrelationships between many environmental issues (such as climate change and acoustics) with vulnerable communities (i.e., low-income, minority, and indigenous and tribal communities). BOEM is stepping up its efforts to understand how offshore energy activities may impact vulnerable communities to determine whether federal activities may have disproportionately high and/or adverse impacts on certain communities. The ESP and CMA will be working with BOEM's environmental justice team to increase engagement with, identify, and study topics that involve vulnerable communities.

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Vantage: A Report on the Acoustical Society Foundation Fund

James H. Miller

This is the third annual "Vantage" report. In it, I provide Acoustical Society of America (ASA) members with an overall view of where the Acoustical Society Foundation Fund (hereinafter referred to as the Fund) has been and where the Fund is headed. Past Vantage reports from 2020 and 2021 and other reports about the Foundation can be found at bit.ly/ATC-Foundation.

I usually give a description of the ASA Foundation Board, a summary of our financial performance in the last year, and a list of our scholarships and fellowships and then close with different ways to give. I briefly cover these topics because I am featuring four people who have benefited from the generosity of our donors.

The Acoustical Society Foundation Board

The Board is made up of dedicated, hard-working volunteers, currently including Freddie Bell-Berti, David Feit, Ron Freiheit, John Hildebrand, Ben Markham, Ed Okorn, Scott Pfeiffer, ASA Treasurer Judy Dubno as an ex officio member, and me as Board chair. I want to especially thank our colleagues Anthony Atchley and Rich Peppin who recently stepped off the Board for their many years of service. The Board makes recommendations to the ASA Executive Council about award levels for each activity the Fund supports. These activities are listed in **Table 1**.

Financial Performance in 2021

Contributions in 2021 to the Fund from members and friends of the ASA totaled $76,293, an increase of 7.8% over 2020. In addition, gains from investments, interest, and dividends totaled $1,578,004. Expenses for the Fund were $323,286, which mostly included the awards, prizes, fellowships, and scholarships. The details of these expenses are covered in **Fund Expenditures in 2021 in Support of the ASA**. Net assets in the Fund at the end

Table 1. *Awards, prizes, fellowships and scholarships supported by the Fund*

William and Christine Hartmann Prize in Auditory Neuroscience
Medwin Prize in Acoustical Oceanography
Rossing Prize in Acoustics Education
Medals Fund
Frederick V. Hunt Postdoctoral Research Fellowship in Acoustics
ASA Early Career Leadership Fellowship
Theodore John Schultz Grant for Advancement of Acoustical Education
Frank and Virginia Winker Memorial Scholarship for Graduate Study in Acoustics
Leo and Gabriella Beranek Scholarship in Architectural Acoustics and Noise Control
James E. West Minority Fellowship
Raymond H. Stetson Scholarship in Phonetics and Speech Science
Robert Bradford Newman Student Award
Robert J. Urick Prize for Best *JASA* Article by a Student in Ocean Acoustics
Robert W. Young Award for Undergraduate Student Research in Acoustics
Robert W. Young Award for International Standards Travel
Royster Student Scholarship Award
Acoustical Oceanography Student Travel Award
Student Transportation Awards
Wenger Prize for the Student Design Competitions

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of 2021 were $13,043,274 compared with $11,638,499 at the end of 2020, an increase of 12.07%.

Fund Expenditures in 2021 in Support of the ASA

In 2021, the Fund was very active in supporting the many activities of the Society. Awards, prizes, fellowships, and scholarships (see **Table 1**) that are supported by the Fund totaled $215,789, an increase of 10% compared with 2020. You can find details of each of these activities at bit.ly/3we52wg. After reviewing these activities, think about any for which you or your students might apply or where you might like to donate.

The support for travel to ASA meetings by students through the Student Transportation Fund is one of the most important activities of the Fund and one of those with the greatest need. Most of the assets in the Acoustical Society Foundation Fund are donor restricted and that limits the amount of travel awards for students. The experience and connections made by students with each other and with more senior members at ASA meetings can change lives. The future of the Society is our students, and so this investment in their careers will pay off for decades. The Foundation Fund awarded $20,510 to students for travel to the fall 2021 meeting in Seattle, Washington, which was only 28% of the funds requested. The need will be even greater in 2022 with ASA's return to two in-person meetings.

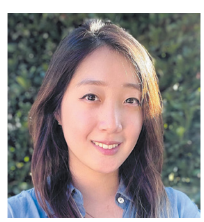
Four recent winners of awards supported by the ASA Foundation Fund were kind enough to send me descriptions of their work that are featured below.

Hannah Rowe is a student at the Massachusetts General Hospital Institute of Health Professions, Boston. She is a recipient of the Raymond H. Stetson Scholarship in Phonetics and Speech Science.

"My research centers around developing acoustic-based clinical phenotypes of distinct speech motor disorders. Quantitative profiles of speech may help to (1) motivate the need to individualize treatment based on a patient's underlying deficits, (2) provide more granular outcome measures for evaluating the efficacy of behavioral and pharmaceutical interventions, and (3) further our understanding of the underlying articulatory mechanisms that contribute to functional communication. With objective, accessible, and interpretable measures of speech function, we may be able improve the confidence of both patients and clinicians in diagnosing and treating speech motor disorders. The Stetson Scholarship has been integral to allowing me to complete my doctoral research in a timely manner and ultimately assisting me in my next step toward becoming an independent academic researcher."

E. K. Ellington Scott is a student at Rensselaer Polytechnic Institute, Troy, New York. He is a recipient of the James E. West Graduate Fellowship for Minorities.

"My name is E. K. Ellington Scott, and I am the 2020–2022 James West Fellow. I am currently a doctoral candidate at Rensselaer Polytechnic Institute in the Graduate Program in Architectural Acoustics. My research focuses on auditory spatial perception, spatial audio technologies, and room acoustics of jazz performance venues. Specifically, my work aims to understand how acoustic energy distribution affects passive and active listening on the stage of smaller jazz venues utilizing auralizations rendered from measured spatial impulse response and hybrid acoustic simulations. The James West Fellowship has allowed me the freedom to combine my passion for jazz and improvised music with my experience as an acoustic consultant. The fellowship has also allowed me to explore other professional institutions to gain experience in communications engineering, software development, and government research."



Miran Oh is a student at the University of Southern California, Los Angeles. She is a recipient of the Raymond H. Stetson Scholarship in Phonetics and Speech Science.

"My research focuses on understanding the role of articulatory coordination and timing stability in encoding phonologically contrastive speech motor tasks. This research leverages real-time magnetic resonance imaging (rtMRI) of the vocal tract during speech production to investigate interarticulator timing of oral and nonoral speech actions such as velum and larynx movements, which have been difficult to quantitatively assess with other instrumental tools. The current investigation of stabilities in coordination illuminates the cognitive representation of linguistic units that are used to structure speech segments and how this timing structure interacts with variations in phrasal structure. The support from the Raymond H. Stetson Scholarship has greatly helped expedite the completion of the proposed research projects, from the facilitation of data analyses and computational modeling to the dissemination of my work in professional settings at ASA meetings as well as at other scientific communities in speech science."

Samuel Underwood is a student at the University of Nebraska-Lincoln. He is a recipient of the Leo and Gabriella Beranek Scholarship in Architectural Acoustics and Noise Control. "The Beranek award has been instrumental in allowing me to pursue multiple exploratory research efforts that otherwise may not have been externally funded. To date, the award has supported my ongoing work for a visual mapping study of flanking sound transmission in wall and door assemblies, a project to develop acoustic applications of building information modeling (BIM) software (recently presented at the ASA meeting in Seattle), and also an effort to re-create Wallace Clement Sabine's original portable organ pipe and stopwatch decay measurement setup (now to be used for outreach with younger students). Moving forward, I hope to leverage these experiences as I begin formulating a proposal for my PhD dissertation in the coming months. I consider myself very fortunate to be able to spend virtually every moment of each day studying, practicing, or teaching in the area of acoustics. This award has granted me the resources to amplify these efforts even further."

What Would You Like the Foundation Funds to Do?

The Fund does a lot of good in supporting the ASA mission. But we can do more. If you have an idea about where the Fund can make a difference, let's start a conversation. I would enjoy hearing your ideas and discussing how we might implement them.

- Do you feel strongly about acoustics education?
- Do you want to make a difference for early-career acousticians?
- Do you want to support the ASA's commitment to increase racial diversity, equity, and inclusivity in acoustics?
- Do you think emerging research in one of our technical areas needs a kick start?
- Are you excited about standards?
- Do you want to recognize a pioneer in acoustics or an outstanding teacher/mentor by creating a fund and naming it in their honor?

Ways to Give

Donors have several options for giving to the Fund, and they include

- Outright gifts of cash,
- Publicly traded securities,
- Life insurance,
- Bequests,
- Pooled income funds,
- Charitable trusts, or
- Charitable annuities.

For more information on these giving options, visit bit.ly/3wcViCG.

As you can see, the Acoustical Society Foundation Fund is doing important work for the ASA with the generous support of our donors. Please reach out to me at miller@uri.edu if you would like to learn more about how to make a difference in acoustics.

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Student Challenge Problem 2022: Additive Manufacturing and Acoustics

Christina J. Naify and Michael R. Haberman

Introduction

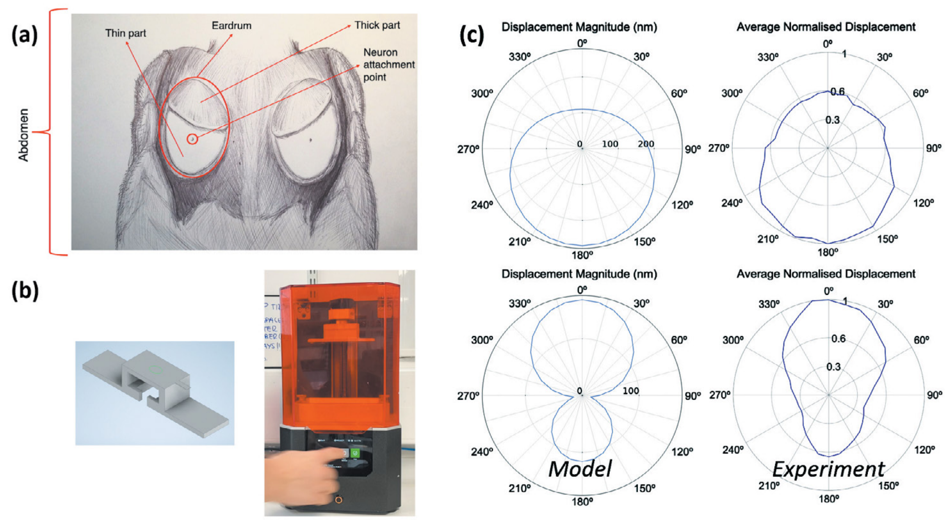
In early 2022, the Acoustical Society of America (ASA) announced a student challenge problem on the topic of additive manufacturing (AM) and acoustics. The challenge was sponsored by the Structural Acoustics and Vibrations (SAV) and Engineering Acoustics (EA) Technical Committees (TCs) and funded as a joint technical initiative between both TCs to award prizes to first-, second-, and third-place entries. This perspective summarizes the winning entries, discusses the motivation for setting up this challenge, and provides an overview of the evaluation of the entries.

Award Winners

Twelve video submissions were received. The first prize was awarded to **Lara Díaz-García** (**Figure 1**) who is pursuing a PhD in electronic and electrical engineering at the Centre for Ultrasonic Engineering (CUE) at the University of Strathclyde (Glasgow, Scotland, United Kingdom). Her entry was entitled *Novel Biomimetic Acoustic Sensors Inspired by Insect Hearing* and is a part of the bioacoustics research theme at CUE that focuses on mechanisms of biological acoustic systems to inspire new developments in acoustical and ultrasonic engineering research. Lara received an $800 cash prize and a $600 stipend for travel to attend the 183rd meeting of

Figure 1. *Lara Díaz-García.*

Figure 2. *Images from the first-prize submission by Lara Diaz-Garcia.* ***a:*** *microelectromechanical system (MEMS) acoustic-sensing device was designed based on inspiration from the hearing organ of the nocturnal moth* Achroia grisella. ***b:*** *device was then fabricated using additive manufacturing.* ***c:*** *directional sensitivity patterns of the MEMS microphone at two different frequencies.* ***Left:*** *model results;* ***right:*** *experimental observations.*



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the ASA in Nashville, Tennessee, to present her work as an invited speaker in a special session on AM and acoustics.

Lara's submission presented a microelectromechanical system (MEMS) microphone that was designed to determine the direction of arrival of an acoustic wave for acoustic signals whose wavelengths are much larger than the device itself (i.e., the microphone is "acoustically small"). Such direction finding typically relies on an array of devices that are comparable in size to the wavelength of the incoming acoustic wave. However, some insects are able to localize sound from predators such as bats using acoustically small organs with unique sensing structure.

This is the case of the hearing organ of the nocturnal moth *Achroia grisella* (**Figure 2a**) from which the winning design took inspiration. The moth has a membrane-type ear whose sensitivity has a surprisingly strong dependence on the direction of arrival. A finite-element model of an approximate representation of the moth's sensing mechanism was conducted and a scaled prototype designed. The design was then fabricated using AM (**Figure 2b**), the directionality of the final device was measured, and it compared favorably with the model predictions (**Figure 2c**).

The second-prize cash award of $600 was given to **Natalie Chang** and **Sabine Meurs** (**Figure 3**), both pursuing a Bachelor of Science in biomedical engineering at the University of Michigan (Ann Arbor), for their entry *3D Printing in Biomedical Acoustics Applications*. This submission presented an AM technique to print biocompatible hydrogels. Hydrogels are polymer materials that do not dissolve in water, are highly absorbent and are often used in the delivery of bioactive payloads. Hydrogels have a prescribed stiffness based on their composition, and the stiffness of the material can be changed by activating vaporization of an emulsion inside the polymer using acoustic activation. Chang and Meurs used bioprinting to deposit hydrogels with a defined shape and layering and then spatially localized activation of the payloads using ultrasound.

Figure 3. *Natalie Chang (**left**) and Sabine Meurs (**right**).*

The third-prize cash award of $200 was given to **Arisa Kuramoto** (**Figure 4**) at Waseda University, Tokyo, Japan for her entry *Shakuhachi Reconstruction from X-ray CT Images by Additive Manufacturing*. In this submission, a shakuhashi, which is an end-blown bamboo flute of Japanese origin, was re-created by reconstructing the instrument structure found using X-ray computed tomography (CT) scans and then fabricated using AM. Because shakuhachi are made from bamboo, repairs are extremely difficult, which motivates the creation of replica instruments. The project provided a detailed description of how data from X-ray CT scans, which are capable of mapping a three-dimensional (3D) structure with micron precision, was used to create a 3D computer model of an existing bamboo shakuhashi instrument. The computer model of the shakuhachi was then printed using AM, and the original AM-fabricated instruments were played by a professional musician, demonstrating very similar sound production.

Figure 4. *Arisa Kuramoto.*

Motivation for the Student Challenge

The student challenge was motivated by the recognition that AM, also known as 3D printing, has wide utility across multiple domains in acoustics, including biomedical, musical, engineering, and structural acoustics to name a few (Naify et al., 2022). Because of this broad application base and ease of access to AM technology by most students, a challenge problem asking students to explore the intersection between acoustics and AM had the potential to receive submissions from a significant cross section of the Society and stimulate student creativity.

The SAV and EA TCs posed the following broad problem statement to the student community: "Use additive manufacturing (3D printing) to advance the field of acoustics or acoustics to advance the field of additive manufacturing." The requirements for submission were that the work be done by a current (as of the time of submission) undergraduate or graduate student from any university, with no restrictions on country, discipline, or affiliation with the ASA. Groups of students were allowed to submit together, with all students in the group splitting the prize money equally. Submissions were in the form of a video no longer than five minutes in length, explaining the motivation, concepts, and results of the project. The winning submissions can be found in **Multimedia Files 1-3** (see acousticstoday.org/naifymedia). The due date was May 31, 2022, with the winners decided on June 22, 2022. Submissions were evaluated by a group of judges from a range of TCs, with judging criteria based on clarity, creativity, rigor, and insight.

The organizers of this competition thank all the students for their entries. The judges were impressed by the range, creativity, and rigor of all the entries received. The organizers also acknowledge judges Stephanie Konarski (Johns Hopkins University Applied Physics Laboratory, Baltimore, Maryland), Robert White (Tufts University, Medford, Massachusetts), and John Granzow (University of Michigan) who evaluated all the entries. Their time spent evaluating video entries and providing thoughtful comments and discussion on all submissions is greatly appreciated.

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Involvement in the Acoustical Society of America Is Key

Tracianne B. Neilsen and Anna C. Diedesch

Introduction

The past few years have seen many disruptions to our normal routine. This "Sound Perspectives" essay for the Women in Acoustics (WIA) Committee to celebrate the women honored at their luncheons has been delayed and last year's column focused on documenting the experiences of acousticians during the Cov-Sars2 pandemic. All past WIA columns are at bit.ly/AT-WIA.

Changes to the Acoustical Society of America (ASA) meetings and schedules meant that the WIA Committee only honored two women acousticians during 2020 and 2021: Alexandra Tolstoy at the Acoustics Virtually Everywhere meeting in December 2020 and Fredericka Bell-Berti at the Seattle ASA meeting in December 2021. This column highlights their lives and careers as well as their involvement in the ASA, which both say was important in shaping their career trajectories, professional experiences, and personal enjoyment. Their insights and advice are also summarized with the intent of encouraging all women to continue the traditions of excellent science, professional networking, sincere mentoring, development of friendships, and opportunities for service within the ASA.

Alexandra Tolstoy

Alexandra (Alex) Tolstoy received her BA and MA in mathematics from George Washington University, Washington, DC, and PhD in applied mathematics from the University of Maryland, College Park. In 1980, her first research position was in underwater acoustics at the Navy Research Laboratory (NRL), Washington, DC, where she became a leader of the matched field processing and inversion efforts. She first attended and gave a presentation at the ASA in 1981.

After many productive years at the NRL, Alex became a senior research scientist with Integrated Performance Decisions, Inc., Middletown, Rhode Island, in 1994. She then became an affiliate faculty at the University of Hawai'i, Honolulu, and founded ATolstoy Scientific, Inc. Alex was prolific in authoring or coauthoring scientific papers, won the Alan Berman Publication Award for the best paper in the US Navy Information Technology Division in 1988, contributed to the Time–Life Series *How Things Work: Oceans* (Golden et al., 1991), and authored the book *Matched Field Processing for Underwater Acoustics* (Tolstoy, 1993). She holds two patents for the matched field processing tomography techniques that she developed.

In the ASA, Alex was involved first in the Underwater Acoustics Technical Committee (TC) and then also in the Acoustical Oceanography TC after it was established. Alex was elected an ASA Fellow in 1994 and is a member of many other scholarly societies.

Around 1992, Alex realized that there were not many women in many of the TCs, and even the TCs that had many women who were well published did not have many women ASA Fellows. Alex felt that it was the right time for the ASA to organize something that would get the women together, to realize they are not alone, to increase the visibility of women, to provide opportunities for networking, and to overall make things more congenial. The then-current ASA President Hank Medwin agreed that women were often getting overlooked in the ASA and agreed to establish an ad hoc committee of WIA to discuss ways to increase visibility, improve networking, and promote women in the Society. Alex was the first chair of the ad hoc committee. She is pleased with how things have changed for women in the ASA since then and feels like we have made progress toward the ultimate goal that "your contributions should count independent of if you are a man or a woman." For more on the history of the WIA Committee during the first 25 years, see bit.ly/3On5IIk.

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Alex retired from acoustics in 2012 and has become an internationally acclaimed artist (see cover). She began painting in 2007, took some classes, and fell in love with watercolors. Her paintings are regularly exhibited both nationally and internationally. She painted a special cover for the fall 2018 issue of *Acoustics Today* and shared her painting "In Tune" (see bit.ly/3pKJUg0) for the virtual booth of the WIA Committee at the December 2020 Acoustics Virtually Everywhere online meeting. Alex encourages us all to pursue artistic activities because they help expand your outlook and interests and keep your mind active. She recommends finding someone whose art you like and taking a class from them, which is how she started with watercolors. Her advice: "You really don't know what you are capable of until you do it."

Fredericka Bell-Berti

Fredericka (Freddie) Bell-Berti was honored at the WIA luncheon in December 2021. Freddie received her PhD from the City University of New York, New York, in speech and hearing sciences. Her early work focused on using electromyographic recordings to study muscular function in the velopharyngeal system and the tongue, a relatively early use of lingual electromyography (EMG). Freddie's thesis work was carried out at the Haskins Laboratories, New Haven, Connecticut, under the direction of Katherine (Kathy) Safford Harris. Freddie coedited the book *Producing Speech: Contemporary Issues* (Bell-Berti and Lawrence, 1995) and has authored and coauthored many well-cited articles about speech production. Freddie was a professor at St. John's University, Queens, New York, from 1980 to 2014 and served as chair of the Department of Communications Sciences and Disorders from 2001 to 2010; she is now a professor emerita.

Freddie feels blessed to have been mentored by Kathy, who introduced Freddie to the ASA as a relatively new graduate student. At the spring meeting in Philadelphia in April 1969, Freddie was amazed at the warm welcome as she registered and then awed by the incredible session on speech perception. Freddie has been a regular attendee and presenter at the ASA since her first presentation in 1972. Of those early years, she remembers that "being accepted as a member of the scientific community with no one asking what degrees I had" convinced her that the ASA was a great place to be. Freddie has continued the tradition of excellent mentoring for more than 100 student research projects, the majority of which were carried out by female students. More than 20 of those students have presented their work at ASA meetings.

Freddie became an ASA Fellow in 1991 and has served on several committees including the Executive Council, ASA Foundation Board, Speech Communications TC, Nominations Committee, Tutorials Committee, Women in Acoustics Committee, and Medals and Awards Committee. Additionally, Freddie served as chair of the Committee on Education in Acoustics (1994–1997), the Long-Range Planning Committee (2000–2003), and the Committee on Prizes and Special Fellowships (2012–2014). Freddie continues to be active in the ASA and has just completed service as the chair of the Committee on Archives and History (2016–2022).

Freddie's involvement in her church, the Eastchester Presbyterian Church in the Bronx, New York, began decades ago but has increased dramatically since her retirement. She currently serves as Clerk of Session at the church and served on the Board of Directors of the church's afterschool program for many years. Freddie is active in the Presbyterian Women's Group at the church and is involved in many other activities. Freddie is also a member of the Board of a new nondenominational Fourth Day program, Footsteps in the Sand, a lay-led organization to strengthen church leadership.

Involvement in the Acoustical Society of America

Alex and Freddie both shared their thoughts about how the ASA has helped them over the years, how the ASA has evolved, and offered advice for those early in their careers.

Science

From Alex's first ASA meetings, she has been impressed with the quality of the presentations and the interesting results that are presented. She enjoyed sharing ideas with knowledgeable, accomplished people. Freddie also expressed this sentiment: "One of the joys of being at ASA meetings over the years has been the chance to discuss science with folks from around the world and never having to worry that an idea I expressed would appear in someone else's work." The high degree of integrity and respect promotes scientific inquiry at the highest levels.

The opportunity to network with others in your field is a key benefit of participating in ASA meetings. A fundamental part of networking is letting people know what you have done and sharing your ideas. One way to do this is to attend meetings of the TCs, contribute to the discussions, and, in particular, volunteer to chair special sessions at upcoming meetings. Although networking often requires effort and sometimes going out of your comfort zone, the importance of developing a network of peers and senior people in your field is extremely important. For more networking tips, see bit.ly/AT-Nielsen.

Mentoring is an important responsibility of all acousticians and other scientists, engineers, and professionals because it advances both research and professions. Alex mentioned how important it is to find a mentor who is more senior than yourself, knows how things are done, and is willing to share advice: "A mentor is also someone who looks out for you and thinks of you when opportunities arise." Both Freddie and Alex are grateful for those who mentored them and encourage everyone, at any level, to find opportunities to mentor others. ASA meetings provide a wonderful opportunity to mentor others, such as the Students Meet Members for Lunch Program, the student reception, the ASA school, and early-career events. An excellent article about mentoring that is helpful for both mentors and mentees was published in *Acoustics Today* (Gee and Popper, 2017).

Social

Although networking and mentoring have a social aspect, both Alex and Freddie stressed how grateful they were for opportunities to socialize and make friends through the ASA. Freddie described it this way: "I've made friends — folks I would never have gotten to know any other way. And I don't mean 'acquaintances' — I mean real friends, folks whose families I know — or know a lot about; folks I'll see at meetings and other places." These friendships develop over time and are a treasured part of ASA meetings. Breaks during sessions and the meetings' socials are a great place to meet new people and chat with those we know. However, those of us who have been participating in the ASA need to conscientiously look out for those who are new, talk to them, and introduce them to others.

Service

The ASA also provides many volunteer opportunities to serve on technical and administrative committees. Service on these committees provides a way to meet people in and beyond your area of specialty, gain an understanding of how the ASA operates, and develop an appreciation for the many who contribute so much time and energy to making the ASA a wonderful professional home. A list of all the committees and a form to indicate your desire to volunteer are found at acousticalsociety.org/volunteer.

Summary

The WIA Committee was grateful for the opportunity to honor Alex Tolstoy and Freddie Bell-Berti and appreciate their scientific contributions, mentoring, friendships, and service. They have both been great examples, role models, and friends to many, especially to those in the ASA. We sincerely hope that their experiences will prompt all of us to be more involved in the ASA and to be inclusive and welcoming to others as we strive to promote the core values of the Society, which were recently approved by the Executive Council and posted on the website at acousticalsociety.org/policy-statements.

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Studying Acoustics Abroad: Exciting Opportunities for Young Acousticians

Erik Alan Petersen

Collaboration is an essential component of modern science! It allows researchers to pool resources, minimize redundancy, and bolster the quality of work for all participants by enabling them to ask research questions that require broad expertise to answer. Moreover, international collaboration, which may well start with studying or working abroad as an early-career acoustician, opens opportunities to participate in the global community of scientists during a pivotal time in one's career. These experiences make a researcher worldly in their discipline and may facilitate future collaboration with international contacts with diverse cultural backgrounds.

I am the *Acoustics Today* (*AT*) 2022 intern. As part of my internship, I will be writing several articles about the experiences of graduate/early-career training abroad. This first article is focused on individuals who were United States based and went to another country; another article will tell the stories of students who have come to the United States.

The overwhelming majority of people I spoke to went to study and work in Europe. Focusing on Europe is not intentional. In fact, I am still anxious to speak with people who went to other continents as their experiences may be unique due to differences in culture both in the lab and in society as a whole. If you are willing to share your experiences, please send me an email.

Inspired by my doctoral research in France, my goal is to speak with a variety of Acoustical Society of America (ASA) members to hear the stories of other early-career acousticians who have gone abroad to study or work. These vignettes capture not only the excitement and reward of training abroad but also the hurdles that everyone inevitably experiences. I am hoping that this article encourages younger ASA members to consider these opportunities and be inspired by the stories of their colleagues who have gone abroad for their master's, PhD, and postdoctoral training.

Philip Robinson (Research Lead, Audio Presence, Facebook Reality Labs Research, Redmond, Washington; see bit.ly/3UfxU3g) funded his PhD research by collaborating with foreign research groups. While a PhD student at Rensselaer Polytechnic Institute, Troy, New York, Philip applied for grants, landing him, sequentially, at Hanyang University, Seoul, South Korea; École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland; and Aalto University, Espoo, Finland, on a Fulbright, noting that, "if you arrive with some funding, it is a lot easier for professors to host you" (personal conversation, 2022). By cobbling together different funding sources, Philip was able to complete his PhD, emphasizing that there is a huge degree of uncertainty during that stage of life.

Currently, Philip oversees a research group with citizens from a dozen nationalities, including some with geopolitical tensions. His time abroad nurtured a certain mental flexibility and empathy that helped him *relate to people from different backgrounds, making him a more effective and compassionate team leader*. He advises early-career acousticians that "there are more opportunities out there than you know about. Apply for everything and do it, talk to everyone in the ASA, and be bold, the scarier and crazier the better" (personal communication, 2022).

However, piecing together funding for a PhD may not be to everyone's liking. Instead, completing a master's degree abroad is one popular path; tuition is considerably lower in many countries compared with that in the United States. Additionally, it is often possible to secure funding through an academic/industry partnership or internal research grants, although certain visas may restrict the maximum working hours per week. I spoke with **Chemay Shola** (master's student, Technical University of Denmark, Kongens Lyngby) and **Aaron Geldert** (master's student, Aalto University), who both opted to enroll in two-year master's programs.

Aaron comments, "I had no clue I would like it as much as I did and learn as much as I did" (personal communication,

https://doi.org/10.1121/AT.2022.18.4.76

2022). Chemay, impressed by the strong regional collaboration between the Scandinavian and Baltic countries, found it easier to build connections and network within the acoustics community in those countries. Making friends with locals is harder, so Chemay recommends *meeting people through organized activities* such as a running club. One perk of being enrolled at the foreign institution rather than be a visiting scholar is that the social and economic advantages of *holding student status often includes benefits such as health insurance, subsidized public transport, restaurant vouchers, and student activities.*

Jay Johnson (Cirrus Logic, Salt Lake City, Utah) followed a different path to graduate school abroad. While a PhD student studying underwater acoustics at the University of Texas at Austin, Jay was encouraged to collaborate with a research group at the Université Libre de Bruxelles, Brussels, Belgium. Keen to travel but not necessarily interested in moving to Belgium, Jay conducted on-site research during the summers.

Jay found it *difficult to meet students in Belgium because he was not enrolled in the university*. But when asked if he would do it again, Jay replies "100%!" As parting advice, Jay comments that "most people were initially willing to speak French but quickly switched to English" (personal communication, 2022). He recommends *a deliberate plan to learn the language and culture*. The best approaches are through high-quality classes and language exchange partners.

A common theme about living abroad is that *everyone makes mistakes*. Language mistakes, cultural faux pas, bureaucratic nightmares, living abroad requires determination. **Laura Kloepper** (Visiting Assistant Professor, University of New Hampshire, Durham; see colsa.unh.edu/person/laura-kloepper) specializes in ecological acoustics and, during her PhD at the University of Hawai'i, Honolulu, spent a month as a visiting researcher at Fjord&Bælt, Kerteminde, Denmark (see fjordbaelt.dk/?lang=en) studying harbor porpoises.

Laura laughs about her missteps, in Denmark and elsewhere, emphasizing that we need to "normalize talking about our mistakes" (personal communication, 2022), noting that she continued to collaborate with members of the Danish team for years afterward.

Reminiscing about her experience abroad, Laura advises "say yes to everything! Graduate students might be stressed, but for many, it is actually one of the least structured times you will have in your life before you have a family, house," adding that *this experience helped inform her as a future principal investigator about how different labs operate*.

Sometimes plans change in unexpected ways when abroad. Take **Martin Lawless** (Assistant Professor, State University of New York Maritime College, Throggs Neck, New York) who began a postdoc at Sorbonne University, Paris, France. A problem arose, however, when Martin received an offer for a tenure-track position in the United States during his first week in Paris. With a negotiated start date and a gracious postdoctoral adviser, Martin, who works in architectural and perceptual acoustics, was still able to complete some research objectives before moving back to the United States ahead of schedule.

Besides the science, the attitude in France toward *work/life balance* left an impression on Martin, who says "I didn't work Saturday or Sunday, didn't think about work, and came in on Monday mornings completely refreshed, completely productive" (personal communication, 2022) In reflecting on his time in Paris, Martin is impressed by *the spirit of collaboration and open science platforms*, noting that his position was funded through a consortium of six European Union universities and that a lot of funding requires data to be made publicly available.

While working on her PhD in musical acoustics, **Whitney Coyle** (Associate Professor, Rollins College, Winter Park, Florida; see bit.ly/3zCpwU6) received a National Science Foundation Graduate Research Opportunities Worldwide Grant, allowing her to study at a foreign institution of her choice. Whitney completed her Pennsylvania State University PhD as a visiting scholar at the Laboratoire de Mécanique et d'Acoustique, Marseille, France (see lma.cnrs-mrs.fr).

Like Martin, Whitney found the expectations of *work/life balance required an adjustment*; the building is inaccessible after hours and on weekends, holidays are respected, and frequent coffee breaks are central to laboratory culture. Additionally, Whitney found that the mentorship style, where *PhD students are treated as colleagues and given wide latitude in their research*, was a major change from her experience in the United States.

One complication, however, was that her obligations to complete the dissertation following US graduate school requirements *did not always align with the expectations of a doctoral candidate in the French laboratory*. Whitney advises students involved in multiple institutions to carefully delineate the specific role of each mentor relationship and to "be clear about your goals for going abroad" (personal communication, 2022).

Whitney remarks on another difference between her experience in France and the United States: most *PhD programs in Europe require a master's degree*. Without regular classroom interactions, it was *hard to befriend her colleagues*. But, as time went on, Whitney was able to meet more people while also maintaining a professional connection to the United States by attending ASA conferences.

Whitney also mentions that, like many academics, she *experienced imposter syndrome, which was exacerbated by the foreign environment*; when she didn't understand a topic, she was unsure whether her confusion was a deficit in knowledge or simply a problem of communication. Her advice? "Who cares if you don't know the answer, find it. Go ask, even if it is embarrassing."

The *motivation to study abroad varies from person to person*. Whitney wanted to work with a specific research group. Chemay, on the other hand, wanted to work within the hearing aid industry in Europe; this made a master's in Denmark, a country with a long history of hearing health research, an appealing option. Indeed, Chemay began a part-time internship at the Eriksholm Research Centre, Snekkersten, Denmark, within months of arriving.

Some students are motivated by adventure, learning languages, and expanding their world view, whereas others may be drawn to a country with family connections. Whitney cautions students to understand their motivations and make their decisions accordingly. Similarly, Laura advises students to *develop a concrete plan with measurable objectives of a successful trip*, especially if it is a shorter visit.

Everyone agrees that moving abroad comes with a host of challenges. Plunging into a new culture, learning a new language, navigating bureaucracy; life in a new country takes work that can be an unwelcome distraction from education and social integration.

However, many people found a *supportive network among their colleagues*. Aaron described a community of international students willing to share their experiences navigating shared challenges. And when Whitney had a hostile landlord experience in Marseille, a fellow PhD student was able to help resolve the situation, something Whitney's level of French would not permit.

Success abroad requires seeking help from people who understand the system, speak the language, and can advocate on your behalf through their understanding of the local culture. Many find that the *experience of being an outsider can teach valuable lessons*. For example, Laura and Whitney comment that their *time abroad taught them skills for communicating with people who may struggle with English*. Speaking slowly, articulating, avoiding slang, and rephrasing sentences, when necessary, may be more natural to those who have struggled in a foreign language themselves.

Although everyone I spoke with recounted challenges experienced abroad, the overarching narrative was one of learning experiences that continue to benefit their personal and professional growth to this day.

So, my own most embarrassing moment? Early on, to practice my nascent French, I asked my adviser if he would "like to have the meeting in his bedroom or mine?", having mixed up the word chambre (bedroom) with bureau (office). The embarrassment has long since faded, and I am forever grateful that I had the opportunity to make that mistake.

Acknowledgments

Thank you to everyone who agreed to talk with me about their experiences abroad. Additionally, I appreciate Zane Rusk and Colby Cushing for connecting me with many of these people.

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Bringing the History of Our Fellows into the Modern Age

Ning Xiang and K. Anthony Hoover

The Acoustical Society of America (ASA) has elected its Fellows from outstanding full or associate members who, according to the Bylaws of the ASA (see bit.ly/ASA-Bylaws), have "rendered conspicuous service or made notable contributions to the advancement, generation, promotion, or dissemination of the knowledge of acoustics or the fostering of its practical applications." All Fellows are members of the ASA College of Fellows (CoF; see bit.ly/ASA-CoF).

The Journal of the Acoustical Society of America (*JASA*) publishes the names and citations of Fellows in recognition of their contributions, and these also appear along with other ASA award winners in the spring and fall issues of *Acoustics Today*. Since 2003, the names and citations of new Fellows have been fully documented in electronic form (see bit.ly/ASA-Fellows). However, prior to 2003, the record of Fellows was unclear.

Recently, the CoF Steering Committee realized that many or perhaps even all of the Fellows had been published in *JASA* prior to 2003, and so it launched a campaign to collect the existing undigitized information. The goal was to collate all ASA Fellows and, if possible, their citations in a searchable database that is now available on the same page as the listings for post-2003 Fellows.

The work to develop this database involved two groups: the National Center for Physical Acoustics at the University of Mississippi, Oxford, and the Graduate Program in Acoustics at The Pennsylvania State University, University Park. Two teams were formed to search for the names and citations of Fellows from the first issue of *JASA* in 1930 through 2002. The authors then combined the two datasets to reduce unintended omissions and to best check and collate the information.

The result is a list of 1,281 ASA Fellows elected prior to 2003. Many are acousticians who are renowned for their distinguished service and scientific contributions as part

Figure 1. *Part of the group of organizers of the Acoustical Society of America (ASA) who met at Bell Telephone Laboratories, December 1928.* ***Bottom row, left to right:*** *F. A. Saunders, R. V. Parsons, D. C. Miller, W. Waterfall, V. O. Knudsen, H. Fletcher, C. F. Stoddard, J. P. Maxfield, F. R. Watson, F. K. Richtmyer, and G. R. Anderson.* ***Second row from bottom, left to right:*** *H. A. Erf, H. C. Harrison, J. R. Kelly, R. L. Wegel, H. A. Frederick, N. R. French, C. W. Hewlett, A. T. Jones, I. Wolff, and J. B. Taylor.* ***Third row from bottom, left to right:*** *L. J. Sivian, E. L. Norton, W. A. MacNair, R. F. Mallina, L. Green, Jr., R. H. Schroeter, H. W. Lamson, C. N. Hickman, and D. G. Blattner.* ***Top row, left to right:*** *W. P. Mason, J. C. Steinberg, V. L. Chrisler, K. J. Schroeter, E. C. Wente, and W. C. Jones. Photo used with permission of the ASA.*

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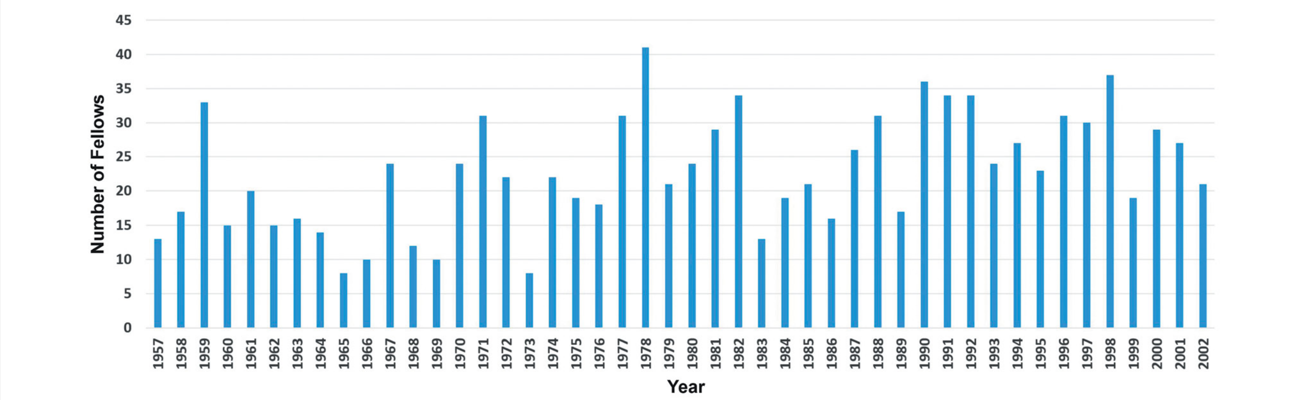

Figure 2. *Distribution of elected Fellows of the ASA between 1957 and 2002.*

of the history of the Society. Here are some insights from reviewing this list.

The Early Years

The earliest published year for Fellows was 1939, seemingly on the Society's 10th anniversary, as documented in the Anniversary Issue [*JASA* 11, 177-178 (1939)]. Some especially notable Fellows are **Harvey Fletcher**, first president of the ASA; **Wallace Waterfall**, first editor in chief of *JASA* 1929–1933; **Dayton C. Miller**, ASA president 1931–1933; **Vern O. Knudsen**, ASA president 1933–1935; **Fredrick A. Saunders**, ASA president 1937–1939; **F. R. Watson**, editor of *JASA* 1933–1939 and ASA president 1939–1941; and **Floyd A. Firestone**, editor of *JASA* 1939–1956, editor in chief of *JASA* 1956–1957.

Other important individuals include **E. G. Boring, Carl Eyring, Fredrick V. Hunt, Erwin Meyer, Paul Sabine, Hugh S. Knowles, Carl E Seashore, Robert Young**, and **Georg von Békésy** (1939), who won a Nobel Prize in Physiology and Medicine in 1960 for his research on the function of the ear. See **Figure 1** for a part of the group of founding members of the Society.

1940s and 1950s

From 1939 to 1957, 235 Fellows were elected. No citations of their respective contributions were available in ASA publications for these Fellows. These included, among others, such luminaries as **Richard H. Bolt** (1941), **Grant Fairbanks** (1941), **Cyril M. Harris** (1946), **Leo L. Beranek** (1947), **Herman Feshbach** (1947), **Hale J. Sabine** (1947), **Ernst Glenn Wever** (1947), **Hallowell Davis** and **Karl D. Kryter** (1953), and **Jozef J. Zwislocki** (1954).

From 1957

Figure 2 shows the distribution of ASA Fellows from 1957 to 2002. During this period, *JASA* published the names of newly elected ASA Fellows along with a citation of their respective contributions. To identify the year of election of a Fellow as accurately as possible, the current pattern of the ASA Fellow election and announcement was followed: newly elected Fellows named in issues published in *JASA* during the first half of the year are identified as having been elected in the previous year, and those published in the second half of the year are identified as having been elected in that year.

For example, **James L. Flanagan** was elected a Fellow of the ASA for "his humorous research studies in speech communications, including both speech analysis and synthesis, and for his excellent contributions to the acoustical theory of speech." His citation was published in *JASA* [31(6), 816 (1959)] and was identified as elected an ASA Fellow in the calendar year 1958.

Max V. Mathews was elected a Fellow of the ASA for "his significant contributions to the use of digital computers in simulating speech processing systems, for his original investigations in speech analysis, and for his theoretical and experimental researches in the auditory detection of signals" as published in *JASA* [33(9), 1249 (1961)]; Mathews was consequently identified as elected an ASA Fellow in 1961.

Before 1957, no citations were given for newly elected Fellows. Between 1957 and 1964, citations for newly elected ASA Fellows were long and detailed, such as those for Flanagan and Mathews. Since 1965, citations for newly elected ASA Fellows have been concise.

Concluding Remarks

The CoF has successfully collected information about the ASA Fellows during the predigital era of the Society. This information enriches the Society's history and reputation and can be remarkably interesting. The elected ASA Fellows are now searchable electronically via the Society's website. Any corrections and/or additions to ASA Fellows' names/years/citations are welcome.

Acknowledgments

The initial search for information in printed copies of *JASA* was performed by Kevin Kwas and Dr. Craig Hickey of the National Center for Physical Acoustics at University of Mississippi and Kyle Hahn and Dr. Steve Thompson of the Graduate Program in Acoustics at Penn State University. We are also grateful to William Hartmann, James Lynch, Arthur N. Popper, and Zhaoyan Zhang who shared their insights on the collated list of ASA Fellows.

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Obituary
Richard R. Fay, 1944–2022

Richard R. (Dick) Fay passed away on September 1, 2022. Dick, a prolific researcher and outstanding teacher, was active in the Acoustical Society of America (ASA) where he led the Animal Bioacoustics Technical Committee, served on many committees, and was associate editor of *The Journal of the Acoustical Society of America*. He received the ASA Silver Medal in Animal Bioacoustics.

Dick's interest in hearing started as an undergraduate at Bowdoin College, Brunswick, Maine, and continued with doctoral studies at Princeton University, Princeton, New Jersey, in the laboratory of E. Glen Wever. Dick moved to the University of Hawai'i, Honolulu, where he was the only postdoc (and only student) ever of Nobel Prize winner Georg von Békésy. While in Hawai'i, Dick met Arthur Popper and they quickly started a highly productive collaboration and close friendship that continued for more than 50 years.

Dick initially sought to understand hearing capabilities of fishes. Although a comparative biologist at heart, Dick chose to focus on hearing in one species, the goldfish. This led to a totally unique body of work examining broad aspects of goldfish hearing. This ultimately enabled Dick to put fish hearing capabilities and mechanisms in a broader perspective of hearing and to make major contributions to understanding the evolution of vertebrate hearing.

Dick's earliest studies focused on questions using psychophysical methods. In these, he trained fish to respond when they detected a sound or when they detected a change in sound to answer a wide range of questions. He then went on to do physiological studies examining the response of the ear to sound. For these studies, Dick designed a unique "shaker table" that allowed him to stimulate the fish in three dimensions, enabling him to examine directional responses of the ear to sound.

Although he continued to study goldfish for his whole career, Dick also investigated the auditory responses of the central nervous system in toadfish, a highly soniferous species. In these studies, Dick and colleagues used physiological and anatomical approaches to understand and map auditory pathways in the brain.

But Dick's work extended well beyond the lab and the classroom. Dick and Art came up with the idea for a set of books on hearing. Although they thought that this would be 8 volumes, the series, known as the Springer Handbook of Auditory Research (SHAR), now has 76 volumes, with Art and Dick as coeditors of every volume.

Reflecting his broad interests in comparative hearing, Dick decided to collect all the hearing threshold data in the literature and put it in one place. This resulted in his classic psychophysics databook in 1988. Although the book has not been updated, it is still an invaluable source of the earlier literature for investigators around the world.

Dick spent most of his career at the Parmly Hearing Institute at Loyola University Chicago, Illinois, where he replaced William Yost, his friend and colleague, as director in 1998. Toward the end of his career, Dick had laboratories both at Parmly and at the Marine Biological Laboratory in Woods Hole, Massachusetts.

Dick is survived by his wife Catherine, children Christian and Amanda, and four grandchildren.

Selected Publications by Richard R. Fay

Edds-Walton, P. L., and Fay, R. R. (2009). Physiological evidence for binaural directional computations in the brainstem of the oyster toadfish, *Opsanus tau* (L.). *Journal of Experimental Biology* 212, 1483-1493. https://doi.org/10.1242/jeb.026898.

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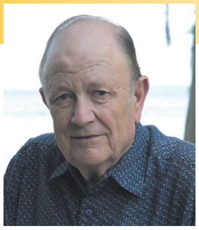
Obituary
David Marvin Green, 1932–2022



David Marvin Green died on July 14, 2022. He served as president of the Acoustical Society of America (ASA), was awarded the ASA Gold and Silver Medals, and was elected to the National Academy of Sciences, among other awards.

Dave first earned an undergraduate degree from the University of Chicago (Illinois; 1952) and then earned BA (1954), MA (1955), and PhD (1958) degrees in psychology from the University of Michigan (Ann Arbor).

While an undergraduate at Michigan, Dave began collaborating with Wilson Tanner and John Swets, and together they (TSG) were responsible for a true paradigm shift in the conceptualization of how sensory systems work and in the methods used to measure the capabilities of the senses. For a century, experimental psychologists had mistakenly viewed sensory systems as possessing "thresholds," categorical barriers that had to be surpassed if a stimulus or a stimulus difference was to be perceived. Also, the methods used to study sensory capacity had been flawed.

TSG argued that there are no thresholds. Rather, repeated presentations of the same weak stimulus (or small stimulus difference) give rise to perceptual experiences of varying magnitude (a stimulus distribution); an observer's task is to decide whether an individual presentation is a sample from that distribution or from the distribution of neural activity associated with no stimulus (or no stimulus difference). This conceptualization was known as signal-detection theory, and Dave became its primary promulgator; his textbook (Green and Swets, 1966) still is widely cited.

An important methodological innovation introduced by TSG was to use well-defined trials, each of which either did or did not contain the stimulus (or stimulus difference), and have the observer respond yes or no on every trial. Thus, every response can be scored as correct or incorrect. Sensory experience became objective, not just subjective.

Another methodological innovation was to plot observers' hit rates (proportion of yes responses on stimulus trials) against their false-alarm rates (proportion of yes responses on no-stimulus trials), plots called receiver-operating characteristics (ROCs). One feature of a ROC is a distinctive shape if the observer has a threshold. After decades of research on dozens of different sensory tasks, no ROC ever has exhibited a threshold like those historically assumed to exist.

A third innovation was to develop ideal observers operating on various aspects of the stimulus and to compare human performance with the ideal.

The impact of these innovations was profound and cannot be exaggerated. Numerous areas of acoustics, experimental psychology, and neuroscience adopted versions of the methods, permitting advances not previously possible. Dave and his collaborators used these methods to study various topics in hearing: masking, intensity discrimination, frequency uncertainty, and binaural processing. For details, see Yost et al. (2021).

Green (2020) believed that one "remarkable" discovery was underappreciated; the area under the ROC curve is equal to the percent correct decisions in a two-interval, forced-choice task using the same stimulus values.

Dave and his wife Marian had close personal relationships with the many students and postdoctoral fellows who studied with him; both were beloved by that group, and both regularly attended ASA meetings. Dave's first wife, Clara, died young; they had four children.

Some adjectives used by past colleagues to describe Dave are creative, insightful, tenacious, disciplined, efficient, principled, respectful, upbeat, and wry.

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Yost, W. A., Patterson, R. D., and Feth, L. L. (2021). David M. Green and psychoacoustics. *Acoustics Today* 17(3), 51-59. https://doi.org/10.1121/AT.2021.17.3.51.

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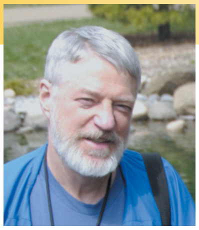
Obituary

Terrence M. Nearey, 1946–2021



Terrance M. (Terry) Nearey, professor emeritus of linguistics at the University of Alberta, Edmonton, Alberta, Canada, and Fellow of the Acoustical Society of America (ASA), passed away on December 19, 2021, at the age of 75.

Terry was born in Neptune, New Jersey, in 1946. He completed his BA in linguistics at the University of Wisconsin, Madison. Following two years of graduate studies at Columbia University, New York, New York, he obtained his doctorate in linguistics at the University of Connecticut, Storrs, in 1977. His dissertation, supervised by Philip Lieberman, examined the acoustic and articulatory properties of vowels, the problem of talker variability (different talkers may produce a given vowel with different articulatory and acoustic properties) and the associated problem of invariance (isolating acoustic properties that allow listeners to distinguish between different vowel categories). In this work, he formulated versions of the *uniform scaling hypothesis*, the idea that most of the variation in formant frequencies across talkers (e.g., between adults and children) can be described using a single multiplicative scale factor. The modeling framework developed to test this theory served as a starting point for much of his later work and influenced many other speech researchers.

In 1983, drawing on evidence from several sources, Terry proposed that vowel-inherent spectral change (VISC) plays an important role in the perception of North American English vowels. Perceptual experiments and statistical modeling demonstrated that listeners attend to changes in spectral properties over time in vowel perception. In his later work, Terry formulated statistical models of formant trajectories in consonant-vowel-consonant sequences, examining how VISC interacts with (and can be distinguished from) the effects of coarticulation introduced by adjacent consonants.

Terry went on to formulate a unique perspective on the relationship between the acoustical, articulatory, and perceptual properties of speech. Difficulties identifying unique, invariant acoustical properties, as required by "strong acoustical" theories of speech perception, led researchers to consider "strong gestural" theories; the answer might lie in a better understanding of the process of articulation or in the motor commands that initiate articulatory movements. Noting problems with both these frameworks, Terry proposed a "double-weak" theory that suggests that the links between phonological categories and their acoustic and articulatory correlates are indirect or "weak," a consequence of the tradeoffs inherent in speech communication. He noted that perceptual mechanisms do not necessarily match our physical models of speech and that the nervous system often solves problems in indirect ways, which he described as "cheap tricks."

Terry was an active member of the ASA throughout his career. He served as associate editor for the speech communication section of *The Journal of the Acoustical Society of America* from 1991 to 1994 and chair of the technical committee from 1995 to 1998. He was a thoughtful and creative person and a source of inspiration to his students and colleagues. He had a wide range of personal interests and constantly expanded his horizons to learn about new research methods and findings. He retired in 2014, remaining active in research collaborations and graduate student supervision until shortly before his death. Terry is survived by his wife Beatrice and three children.

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Obituary
Thomas D. Rossing, 1929–2022

Courtesy of American Association of Physics Teachers (AAPT)

Thomas D. (Tom) Rossing, 93, a mentor, teacher, and author, passed away on July 14, 2022, in West Lafayette, Indiana. Tom earned a bachelor's in physics from Luther College, Decorah, Iowa, in 1950 and a master's and PhD in physics from Iowa State University, Ames, in 1954.

He then worked for three years on magnetic memories with the UNIVAC division of Sperry Rand. In 1957, he became a professor of physics at St. Olaf College, Northfield, Minnesota. From 1971 until retirement in 2005, Tom was a professor of physics at Northern Illinois University, DeKalb. He spent much of his retirement as a visiting professor at the Center for Computer Research in Music and Acoustics at Stanford University, Palo Alto, California.

Tom started in the musical acoustics community while teaching a physics of music class for music majors needing a science credit at St. Olaf College. His contributions to the field of musical acoustics included research on the acoustics of percussion instruments, most notably the timpani, cymbals, the Caribbean steelpan, and bells. His work on the acoustics of bells included taking measurements of ancient Chinese bells in the Shanghai Museum, Shanghai, China, and consulting with handbell makers to develop bass handbells made of aluminum as well as hand chimes, an instrument frequently used in handbell choirs.

Tom's contributions to musical acoustics were on a par with his work in the field of physics education. He was a staunch supporter of physics and acoustics education at all levels. He published articles in *The Physics Teacher* as well as in the *American Journal of Physics*. He wrote a laboratory manual to accompany his *Science of Sound* textbook. His dedication to physics and acoustics education was further demonstrated through multiple endowments, including a gift to the Acoustical Society of America (ASA) Foundation establishing the Rossing Prize that is awarded to individuals who have made significant contributions toward furthering acoustics education.

Tom was a lifelong learner and a self-described voracious reader. While serving as editor of the ASA newsletter *ECHOES*, he wrote the columns titled "Scanning the Journals" and "Acoustics in the News" that included short summaries of articles drawn from his reading pile. He was an associate editor for education for *The Journal of the Acoustical Society of America* (*JASA*) and for musical acoustics for *JASA Express Letters*. He also served as chair of the Technical Committee on Musical Acoustics and was a member of the Medals and Awards Committee.

He was a prolific writer. He authored or coauthored 12 books, mostly on acoustics or musical acoustics, but was also coauthor of a textbook called *Light Science* for use in a class on the physics of the visual arts. He was the author or coauthor of hundreds of scientific papers on topics of condensed matter physics, musical acoustics, and physics education.

Tom was an ASA Fellow and a recipient of numerous honors and awards including the ASA Gold Medal in Acoustics and Silver Medal in Musical Acoustics.

Tom is survived by four daughters, Karen Grandall, Barbara Rossing, Jane Frankenberger, and Mary Rossing, and his former wife Dorothy Rossing as well as two grandsons and two great-grandsons.

Selected Publications by Thomas D. Rossing

Rossing, T. D. (1976). Acoustics of percussion instruments — Part I. *The Physics Teacher* 14, 546-556.

Rossing, T. D. (1994). Acoustics of the glass harmonica. *The Journal of the Acoustical Society of America* 95, 1106-1111.

Rossing, T. D., Russell, D. A., and Brown, D. E. (1992). On the acoustics of tuning forks. *American Journal of Physics* 60, 620-626.

Sundberg, J., and Rossing, T. D. (1990). The science of singing voice. *The Journal of the Acoustical Society of America* 87, 462-463.

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