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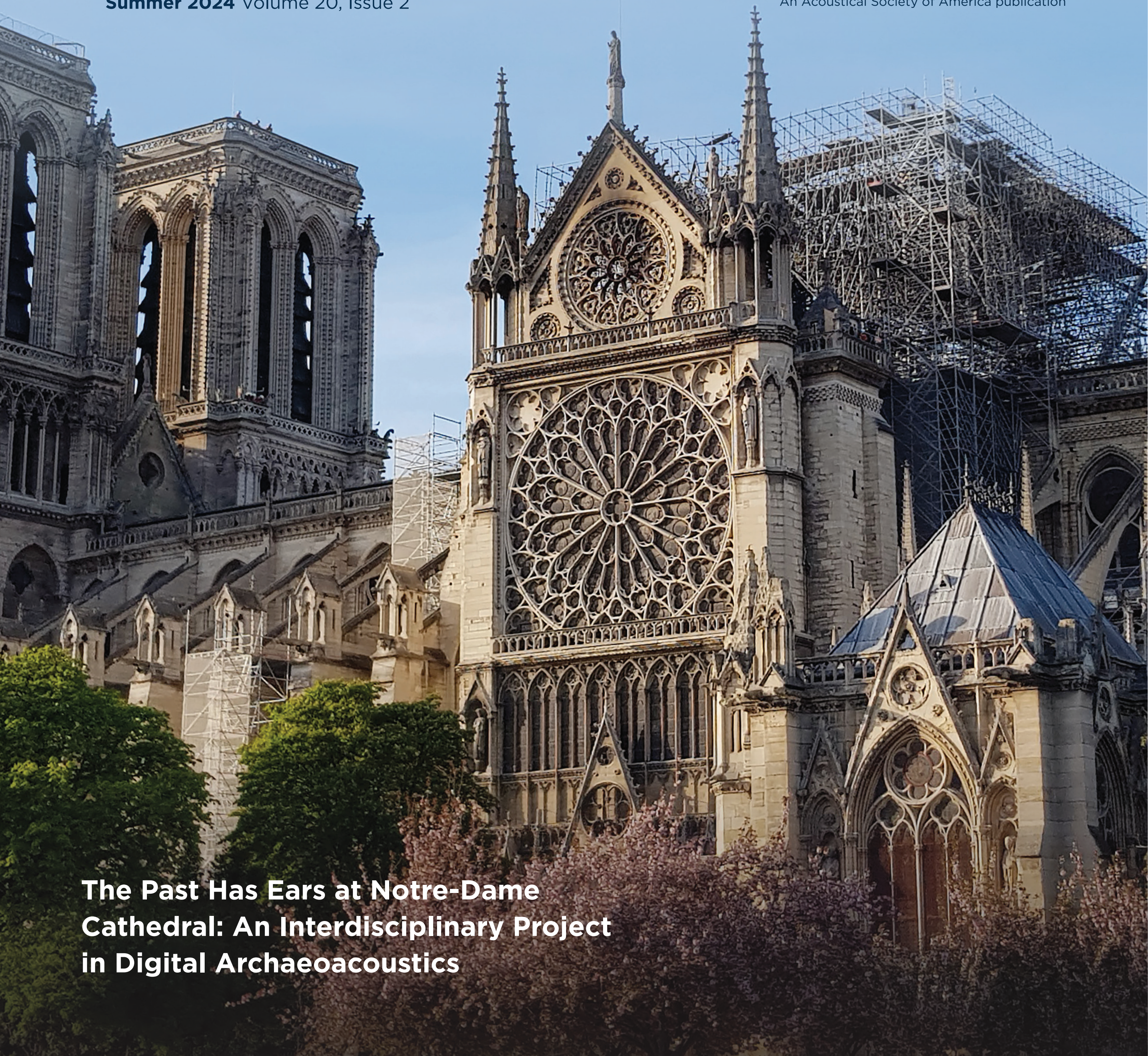

The Past Has Ears at Notre-Dame Cathedral: An Interdisciplinary Project in Digital Archaeoacoustics

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About the Cover

Notre-Dame Cathedral, Paris, 17 April 2019, only days after the devastating fire that was the impetus for the research project "The Past Has Ears at Notre-Dame," exploring the sonic history of this monument. See page 49. Photo by Brian F.G. Katz. Authorized for use as the cover of *Acoustic Today* featuring the article on the PHEND project.

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From the Editor

Arthur N. Popper

The Future of *Acoustics Today*

As my tenure of *Acoustics Today* (*AT*) Editor comes to an end (with the winter 2024 issue), I look back on 241 articles published since I started (and 370 since the start of *AT*), and the many other pieces we have included in "Sound Perspectives." One of my goals as editor has been to have articles that reflect the diversity of our very broad discipline that, hopefully, help all of us learn about, understand, and appreciate the breath of disciplines within the field of acoustics. But the role of *AT* is not only to provide interesting articles but also to inform Acoustical Society of America (ASA) members about our Society, our members, and other issues that members might find of interest.

Of course, turning over *AT* to anyone else is hard, and so I have been very concerned that we find the right person. But with the selection of D. Keith Wilson as the new *AT* editor, I am convinced that we did find the right person. I say this not only because Keith has great credentials as a scholar and an ASA member, but also because he shared with the search committee insightful and interesting ideas for the future of *AT* that I wish I had thought of! What makes Keith even more qualified is that he has written a number of excellent articles for *AT* during my tenure as editor; he understands the purpose and goals of *AT*, and he understands our very broad audience. I look forward to working with Keith so that the transition to our new editor is seamless and he is able to move the magazine forward in new and exciting ways.

This Issue

Following our "tradition" of having a broad array of topics, this issue has six articles that run the gamut from the acoustics of a famous cathedral to the structure and function of harps to communication in hospitals, and to many other things.

The first article is by Melissa Michaud Baese-Berk, Tessa Bent, and Erica Ryherd who write about the interesting difficulties of communication between health professionals and patients in hospitals. Problems arise not only because of the language that the health professionals use but also result from hospital noise, wearing of masks, and many other factors that may not be present in other settings.

The second article deals with autism and indoor sounds, with a particular focus on issues in classrooms for autistic children. In their article, Fernanda Caldas, Samuel Underwood, Bruno S. Masiero, and Lily M. Wang share insights into overall issues for autistic individuals in communication and then relate them to classrooms and their design to make learning easier for the autistic individuals. (For more articles on classrooms and acoustics, see https://bit.ly/AT-Classrooms.)

This is followed by an article by Jordan Cheer and Felix Langfeldt who talk about active sound control. Although Jordan and Felix spend a good deal of their article discussing modern approaches to active sound control, they also provide an interesting historical perspective on the field, which is well over 100 years old.

The fourth article by Lauren A. Freeman discusses the aquatic soundscape. Lauren takes two overlapping approaches in her piece. First, she discusses the importance of the soundscape to aquatic animals and then she talks about the nature of the soundscape itself. Both topics are related and share a story that nicely parallels earlier articles on both terrestrial and marine soundscapes. (For earlier articles, see bit.ly/3vGswzJ)

The fifth article is another that I found while reading *The New York Times*. It discusses the acoustics of Notre-Dame Cathedral in Paris, France, both before and after the devastating 2019 fire. The authors, Sarabeth S. Mullins and Brian F. G. Katz, share a bit of the fascinating history of the cathedral as well as how they have been analyzing the sound and its changes. (For articles about the acoustics of other built spaces, see bit.ly/AT-BuiltSpaces.)

Our final article by Chris Waltham adds to our collection of articles about the acoustics of musical instruments (see bit.ly/AT-Instruments) where he discusses the sounds of the pedal harp. I must admit that I knew absolutely nothing about the sounds of harps, and I found Chris' article a fascinating introduction not only to modern harps but also to the history of the instrument.

Although I don't normally point out the "From the President" column, I do want to urge all members to read this one by Stan Dosso who presents a very interesting and useful overview of ASA programs for students. The column is not only a "must read" for our students and younger members but also for more senior members who might, at some point, have their students participate in one or more of these exciting programs or perhaps host a student who participates in one of our programs.

"Sound Perspectives" starts with "Conversation with a Colleague." This month, *AT* Associate Editor Micheal Dent interviews Eleanor Stride. Eleanor is a bioengineer whose interests are in developing methods to improve drug delivery to patients using bubbles. (For all of our past Conversations, see bit.ly/ATC-CWC.)

We also include a new "Student Challenge Problem in Acoustic Signal Processing" by Brian G. Ferguson, R. Lee Culver, and Kay L. Gemba that should appeal quite broadly.

Finally, as we do after each ASA meeting, we provide a list of members who have been recognized by the Society with various awards.

I am pleased to present links to the sites of two wonderful artists who have each done several very imaginative covers for *AT*. Mark Weinberg, a retired attorney, has posted his *AT* covers at bit.ly/3vrkWJe. Alex Tolstoy, a retired acoustician and ASA member, has posted her covers at bit.ly/43IVPhr. I thank Mark and Alex for truly imaginative and magnificent contributions to *AT* and for being so great to work with.

Stan Dosso

Acoustical Society of America Student Programs

This is my last column as president of the Acoustical Society of America (ASA) because my term ends at the conclusion of the spring 2024 meeting in Ottawa, Ontario, Canada. I will add a few closing words on this at the end of the column, but first I would like to share some thoughts and information on one of the ASA's considerable strengths that I think sometimes flies under the radar.

If you were to ask someone familiar with the ASA what they think are the Society's main programs, I expect almost all would note our internationally leading publications, including *The Journal of the Acoustical Society of America (JASA), JASA Express Letters, Acoustics Today, and Proceedings of Meetings on Acoustics (POMA)* as well as our twice yearly ASA meetings. These are undoubtedly right answers, but the ASA also provides value and support to members and to the field of acoustics in many other ways, including the area of student programs where much innovative and effective work is ongoing.

It's often said that students are the future of science, and this is without doubt true in the field of acoustics. Hence, exposing students to acoustics, encouraging their interest in the field, and engaging and supporting them in the ASA are vital to the future of the field and of the Society. In this column, I highlight two of the ASA's exceptional student programs: ASA School (where I've had first-hand experience) and the Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA) as well as briefly mention a few others.

ASA School

The idea of an ASA-sponsored "school" in acoustics for graduate students and early-career professionals (e.g., see acousticalsociety.org/asa-school-2024) was spearheaded by Brigitte Schulte-Fortkamp and Judy Dubno, who proposed the concept to the Technical Council in 2011. The plan was to hold the School biennially, over the weekend immediately preceding the spring ASA meeting in even-numbered years, a schedule we have kept since the first school was held in 2012 (except for 2020 when the Covid-19 pandemic precluded the meeting). I served as an instructor at the 2014 School, then joined Brigitte and Judy as a coorganizer in 2016; Andrew Morrison was an instructor in 2022 and joined the organizing team in 2023.

In addition to providing presentations, hands-on demonstrations, and mentorship in diverse areas of acoustics, the ASA School program was designed to encourage participants to interact and get to know one another, discuss interests and collaborations, and begin to form professional and social networks with their peers, which we trust will benefit them throughout their careers. We also hope that, in a larger sense, offering ASA School on a regular basis enhances the long-term participation and engagement of students and early-career professionals in the field of acoustics and in the ASA, helping to keep the Society strong.

Building on the interdisciplinary nature of the ASA, the theme of "Living in the Acoustic Environment" was selected for the ASA School. Because the weekend time frame was too short to cover all of the ASA's 13 (now 14) technical areas in acoustics, it was decided to consider roughly half of these at each School, and alternate topics from School to School. However, attendees in all technical areas are welcome at every School, with the goal to learn about areas of acoustics beyond their own specializations.

In addition to presentations/demonstrations by invited instructors, School programs also include group and round-table discussions and professional development sessions. Social aspects include a Friday evening welcome reception, Saturday evening School dinner, breakfasts and lunches, and morning and afternoon breaks, all designed to provide participants with ample opportunities to meet and interact with the instructors and with each other. In fact, over the years, we found (and learned from attendee feedback) that the goals for the School were better met by reducing the number of the instructor presentations relative to other program components. The first School in 2012 had 12 such presentations, which was reduced to 10 in 2016 and to 8 in 2022.

Invited instructors are prominent and diverse acousticians chosen in the appropriate technical areas who also excel in teaching and student mentoring. In all, over the six Schools to date (including 2024), this amounts to more than 50 ASA members who have served as instructors, representing an incredibly talented and accomplished group. We've also had about 350 graduate students and early-career professionals (usually about an 80/20 split) attend ASA Schools to date, and a few attendees at our earlier Schools have later returned as instructors. It's clear at the Schools that participants are engaged and often inspired by the presentations and discussions. I know I am.

To foster personal interaction and mentorship, ASA School attendance is limited to 60 participants. Unfortunately, this has meant that we cannot accept all applicants, particularly as the School's popularity has grown rapidly in recent years. To ensure accessibility, participants pay only a modest registration fee, with the weekend's accommodation and meals provided by the ASA, the ASA Foundation, and industry sponsors. School participants are required to attend and author/coauthor a talk or poster at the following ASA meeting (a list of these is shared so participants can easily attend each other's presentations).

One of the goals of the ASA School is to encourage and promote diversity and inclusivity, which are considered in developing programs and determining attendees. Although continued efforts are needed, we have seen progress such that, for example, for the 2024 School, 58% of attendees identify as male, 37% as female, and 5% as other or preferred not to answer (with instructors and organizers 50/50 male/female). Furthermore, 42% of attendees identify as White, 27% as Asian/Asian American, 11% as Hispanic/Latino, 5% as Black/African American, and 4% as other. Perhaps not surprisingly, the majority (85%) come from the United States and Canada, whereas 7% are from Europe and from Asia and 2% are from Australia.

Our observations and student feedback indicate that the ASA School is achieving its goals and is valued and appreciated by the attendees (and instructors). Participants frequently extoll the presentations and professional development sessions in broadening their interest and understanding in acoustics. However, the comments we hear most commonly involve the significance to individuals, many attending their first ASA function, meeting and connecting with a peer group in acoustics, and feeling welcome in and part of the ASA.

Summer Undergraduate Research or Internship Experience in Acoustics

Although the ASA School is aimed at graduate students and young professionals, SURIEA focuses on undergraduate students in underrepresented groups from across the country in an effort to inspire the next generation of acousticians and make the ASA and the field of acoustics more inclusive, diverse, and welcoming (see acousticalsociety.org/suriea).

SURIEA was developed under the auspices of the ASA Committee to Improve Racial Diversity and Inclusivity (CIRDI), which was formed in 2020. CIRDI was charged with developing initiatives and activities to address the fact that the composition of the ASA membership does not reflect the demographics of the United States population in terms of people of color, who are significantly underrepresented in acoustics and acoustics-related fields (see bit.ly/39rijJ7). This results, in part, from the lack of opportunities for underrepresented groups to be exposed to acoustics as a possible career path at the critical undergraduate stage where such decisions are often made. To address this, CIRDI proposed that the ASA establish and manage a summer research and internship program in acoustics for undergraduate students in underrepresented groups, which was realized when SURIEA was formed in 2021 with Tyrone Porter as committee chair and Peggy Nelson as vice chair.

SURIEA is an intensive summer program in acoustics that emphasizes training, mentoring, and practical experience in preparing students for graduate studies and/or careers in acoustics. SURIEA applicants must be undergraduate students who identify as Black or African

American, Hispanic or Latino, Native American, Native Hawaiian or Other Pacific Islander, or Alaska Native (participation in the program to date has been 55% Black/African American, 39% Hispanic/Latino, and 6% other). The program consists of three distinct elements: classroom sessions, hands-on training, and academic/career development. Through these, interns learn how to conduct acoustics research and analyze acoustic data and how acoustic standards are used in industry. They also contribute meaningfully to an ongoing research project or industry application.

The centerpiece of SURIEA is a paid 12-week internship where each student works in person on a research or industry project in acoustics with an individual mentor at the mentor's home institution (because this requires students to relocate for the summer, a housing allowance is provided). A one-week, in-person short course on the Fundamentals of Acoustics precedes the internships each year to provide an introduction to acoustics and baseline knowledge relevant to all areas of the field. This course also brings all of the participants together at the start to begin to build support networks with each other and the SURIEA instructors and to engage and identify as a cohort. During the summer internship, participants and instructors also meet virtually as a group each week to refine professional skills, practice scientific/technical oral and written communication, and strengthen support networks. Finally, after the internship, students attend an ASA meeting where they again meet in person as a cohort and can participate in student-led activities and social events as well experience the ASA's broad technical program in acoustics. Students are encouraged to present a talk or poster on their internship at the ASA meeting, although this is not a requirement of the program.

Mentors in the SURIEA program are chosen from applicants in academia or industry based on their ability to integrate a minority student intern into an active and supportive research group and to provide opportunities for scientific, practical, and career development. Mentors also assist in finding housing, and are expected to take part in all aspects of SURIEA over the summer and to maintain relationships with students in the program remotely and at conferences over the next few years. Mentors are not expected to provide funding for the student or the program, although some do so voluntarily. The ASA is committed to funding five students in the SURIEA program each summer, and thanks to the generous support of mentors and external sponsors, additional students are accepted each year, although the number of applicants exceeds the capacity of the program. SURIEA has run since 2021 with up to 15 students in each of the first three summers and in the 2024 summer to come. Internship projects are diverse and often fascinating, including, as a few examples, studying humpback whale songs, modeling ultrasonic beams, investigating social identifiers in speech, analyzing hearing loss with computational models, mapping the human spinal cord with passive acoustics, developing a cell phone app to track urban noise, and auralization in room acoustics.

I have attended SURIEA get-togethers at ASA meetings and can attest to the enthusiasm for acoustics, sense of identity and pride in their cohort, and appreciation for the program among the students, many of whom seriously consider further studies or a career in acoustics. SURIEA is, without a doubt, one of the most innovative and progressive student programs I know of anywhere.

Other Acoustical Society of America Student Programs

In addition to the ASA School and SURIEA, highlighted here, the Society has many other programs for students. One is the ASA Student Council (see bit.ly/3TYFaU7), which includes members from each of the ASA technical committees (TCs) who transmit information and represent student interests within their TC. The Student Council organizes several student events at each ASA meeting, providing a welcoming and active peer/social group. Serving on the Student Council also provides leadership opportunities and an introduction to the ASA organization; many ASA leaders started out on the Student Council.

The ASA has an extensive program of fellowships and scholarships to recognize excellence and provide financial support for graduate/undergraduate students and postdoctoral scholars in various acoustics disciplines, in some cases supporting underrepresented groups. The Society also offers a variety of student transportation and conference attendance grants and subsidies. Many TCs offer Best Paper Awards to students or early-career presenters at ASA meetings, and *POMA* offers five student awards for conference papers published after each meeting. For information on all of the programs above, see bit.ly/4aev9Yx.

Finally, in recognition of the growing importance of education initiatives, the ASA Committee on Education in Acoustics is being reorganized as a new Administrative Committee on Outreach and Education plus a new Technical Specialty Group (TSG) on Education in Acoustics. A TSG organizes technical sessions at ASA meetings in new or evolving areas not within the scope of existing TC, and can be the first step in establishing a new TC. The new committee will support activities promoting acoustics education at all levels, such as developing educational tools for teachers and planning outreach activities for school-age students at ASA meetings. The new TSG will focus primarily on education at the university level but will also include younger students. A key ASA staff member in all this is Education and Outreach Coordinator Keeta Jones, who works closely with various groups to propose and implement activities for promoting acoustics.

Signing Off

Returning now to the end of my tenure as ASA president, it has been a privilege to serve the Society that represents my professional home and is one of the highlights of my career. I have particularly appreciated working together with many dedicated and exceptional members and staff. Although many more deserve recognition, I must particularly acknowledge ASA Past President and President-Elect Peggy Nelson and Barbara Shinn-Cunningham, respectively, Vice President Ann Bradlow, Treasurer Judy Dubno, ASA Executive Director Susan Fox, and ASA Director of Operations Elaine Moran. Finally, I thank *Acoustics Today* Editor Arthur N. Popper for his expert assistance in writing these columns.

Communication in Medical Settings

Melissa Michaud Baese-Berk, Tessa Bent, and Erica Ryherd

Introduction

Communication between health-care providers and their patients as well as among providers themselves is crucial for optimal health outcomes. Clear communication is required for providers to understand the symptoms a patient is experiencing and to determine an appropriate diagnosis. Similarly, clear communication is required for providers to hand off care to other providers in, for example, hospital settings. It is also necessary for development of a treatment plan that can be executed by the provider and/or patient. In short, quality communication is a prerequisite for quality health care.

However, speech communication in medical settings differs from the ways in which it is usually studied, which is generally in quiet laboratory-based settings. For example, hospitals are noisier than quiet sound booths. However, communication in medical settings is distinct, even, from many other "normal," nonlaboratory communication scenarios. For example, although educational settings are also typically noisy, medical settings have features that increase the challenge of communication, even compared with other everyday scenarios. For example, patients may be exposed to less familiar medical terminology during conversations. Patients may be anxious or may be speaking with a provider whose speech patterns are unfamiliar. Each of these, and many other factors, can impact the success or failure of medical communication.

In this article, we review some special considerations for communication in medical settings, focusing especially on patient-provider interactions. We include doctors, nurses, and other medical professionals as providers in this article because they face similar challenges in terms of medical communication. Our focus is on two aspects of medical communication: speech perception, or how listeners understand the words and sentences they hear, and speech production, or how these words and sounds are produced. After summarizing the special considerations of medical communication, we discuss specific challenges known to impact speech perception and speech production and how these challenges may be especially acute in medical settings. We conclude with a call for more research in this area, specifying areas that could especially benefit from additional investigation.

Special Considerations for Communication in Medical Settings

Although the functions of medical settings are similar to those in other indoor environments, they also typically have specific properties that could hinder how individuals are able to communicate in these environments. Chief among these properties are the physical contexts in which medical communication takes place and the linguistic context of communication in these settings.

Physical Contexts

Anyone who has spent even a short time in a hospital setting can tell you it is a noisy place compared with a quiet office space. Machines in the room beeping, the blaring television in a neighbor's room, a nurse's squeaking sneakers in the hallway, and pages for doctors over intercoms can all contribute to noisy environments. The sheer number and complexity of noise sources in hospitals leads to sound environments that are louder than desired overall and that fluctuate widely over short timescales. Indeed, noise levels in American hospitals frequently exceed recommendations from the World Health Organization (WHO) (e.g., Busch-Vishniac, 2019) and other advisory bodies. For example, the WHO recommends that daytime equivalent sound pressure levels (L_{eq}s) should not exceed 30 dB(A) (Berglund et al., 1999). However, overall hospital noise levels are significantly higher than this. In one study, overall hospital noise was measured at a L_{eq} of 50-60 dB(A). Similarly, operating rooms, emergency rooms, and even intensive care units (ICUs) demonstrate values far exceeding the recommendations (Ryherd et al., 2008). Furthermore, noise levels are not necessarily improving with time despite these

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recommendations (Ryherd et al., 2011). The challenge of hospital noise is not restricted to the United States. A recent, systematic literature review of hospital noise articles from other countries showed that noise levels measured in nearly all locales were higher than recommended, ranging from 37 to 89 dB(A) in the daytime and 39 to 69 dB(A) at night (de Lima Andrade et al., 2021).

Indeed, the issues surrounding hospital noise have been the focus of substantial research. Mounting evidence reveals the potential impacts of poor hospital soundscapes on both patients and hospital staff. Poor soundscapes result in decreases in patient satisfaction, sleep disruption, and undesirable physiological impacts such as increased heart rate and decreased wound healing (Busch-Vishniac and Ryherd, 2023). Ryherd et al. (2012) found that the staff report that they experience annoyance, reduced concentration, disruption of tasks, alarm fatigue, and physiological stress responses due to the noisy soundscape. In short, the hospital soundscape too often falls short of the calm, relaxing environment it aspires to be (Busch-Vishniac and Ryherd, 2019).

The challenge of noise isn't just one of annoyance or stress for the occupants: it can impede communication. This challenge can be exacerbated if the provider (or patient) is wearing a mask, which can result in acoustic modulations to the speech and a lack of visual information from the speaker's mouth. For example, when listening to speech, we often use both visual information and acoustic information to process that speech (e.g., Rosenblum, 2008). Another issue is that masks act as a filter for speech, blocking some acoustic information that might be present without a mask (McKenna et al., 2022). Indeed, filtering of sound was made especially clear to many individuals during the Covid-19 crisis, when suddenly, without much practice, many of us were communicating exclusively through masks. Again, communication challenges in health care settings are not restricted to the United States. An article published through the International Hospital Federation states, "Regardless of the country and culture, it is clear that challenges with communication in hospital environments are shared" (Cirino et al., 2021).

Linguistic Context

In addition to the challenges of the physical environment, medical communication is rife with linguistic challenges. Specifically, most patients do not have medical training. Therefore, much of the precise medical terminology used to describe diseases or procedures is likely to be less familiar to a patient. Even words that *are* familiar (e.g., "cancer") are likely to be lower in frequency of use for most patients. In speech science, frequency is a quantitative measure of how often a word appears in some set of speech or writing and is known to impact speech processing. Below, we describe in more detail the specific challenges to two key aspects of speech communication in medical settings, speech perception and speech production, and how these challenges can impact communication.

Speech Perception Challenges

Speech in Noise

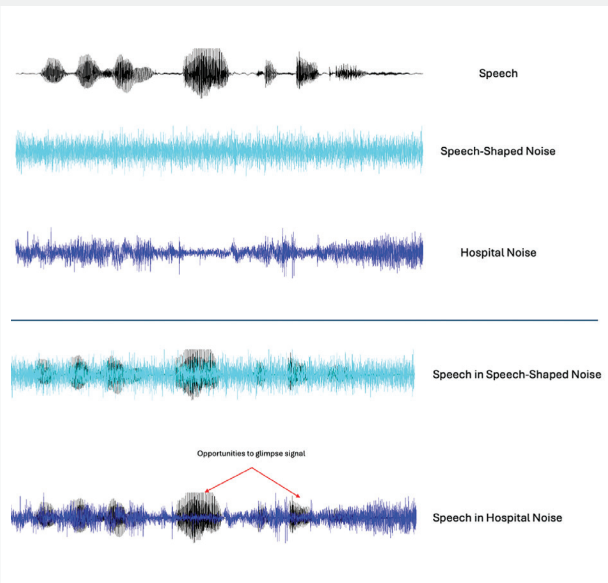
Speech perception in noisy situations has long been known to be challenging for listeners (e.g., Cherry, 1953). "Noise" in speech perception work is often divided into two categories. Energetic masking is where the signal is masked by specific spectral and temporal properties of the noise. In contrast, informational masking is where, in addition to energetic properties of the noise, listeners are also exposed to linguistic information that they must ignore to understand the speech signal. For example, construction noise is typically thought of as energetic masking, whereas conversations surrounding someone in a crowded bar is thought of as informational masking.

Both types of masking are known to impact speech perception, although this impact can vary as a function of specific properties of the noise (Leibold et al., 2019). Informational masking produced by a single talker is often much more challenging for listeners than a masker that includes many talkers (Van Engen and Chandrasekaran, 2012). That is, it is difficult to ignore specific words or phrases produced by a single competing talker because you can easily discern those words and phrases. However, when listening to speech in a masker that includes many talkers, the talkers' voices may blend. This creates a background sound without much distinct speech. Similarly, it is more challenging to decode speech presented in an energetic masker that shares similar spectral properties to speech than in a masker that consists primarily of frequencies much higher or much lower than those typically present in speech.

In medical settings, especially in hospitals and long-term care facilities, the noise in the environment often contains properties of both informational and energetic masking. For example, a patient may hear the voices of other care providers at the nurse's station outside their room. Simultaneously, they may hear HVAC noises, carts squeaking, and doors slamming.

The unpredictable nature of hospital noise may also make it more challenging for listeners, and especially older listeners, to understand the signal through the noise. That is, the differences in amplitude of the noise across time may allow younger listeners to "glimpse" the target speech in periods when the noise is not as loud, allowing them to use context cues to better interpret and understand the target speech (**Figure 1**). However, older adults have a reduced ability to utilize this fluctuation in noise because they may demonstrate challenges with several temporal aspects of auditory processing (e.g., duration discrimination; Anderson et al., 2018). It is likely, then, that older adults may struggle more with other tasks that require temporal processing such as the "glimpsing" process described (see **Figure 1**). These issues are also often compounded by age-related hearing loss in older adults (Anderson and Karawani, 2020).

Figure 1. *Waveforms of speech.* ***Top:*** *speech-shaped noise (e.g., noise similar to white noise but louder in lower frequencies, similar to speech) and hospital noise.* ***Bottom:*** *waveforms of speech in both speech-shaped noise and hospital noise. Note that the "valleys" in hospital noise allow a listener to "glimpse" the speech signal, which is not possible in speech-shaped noise.*



Frequency and Familiarity of Words

It is also likely that the content of the speech patients hear in hospitals impacts their ability to understand the message being conveyed to them. Here, we describe basic findings around frequency and familiarity of words in general and then discuss how this may especially affect medical communication. Substantial previous work has demonstrated that both word frequency and word familiarity impact speech perception (e.g., Colombo et al., 2006).

Familiarity, in general, is a key driving force for improved speech perception. Parents or caregivers for small children are often able to understand these children's speech better than strangers. Similarly, experience with a family member who has a speech or language disorder may help a listener better understand their speech. However, familiarity also helps speech perception more broadly. Listeners are better able to transcribe familiar voices than unfamiliar voices, even when those voices are presented in challenging listening situations, like noisy environments (Johnsrude et al., 2013). Furthermore, listening to familiar accents improves perception of both specific speakers the listener has heard before and novel speakers who have the same accent.

Familiarity exists not only at the level of voices or accents but also in terms of the words (or lexical items) that a listener hears. Substantial previous work has demonstrated that listeners recognize familiar words more quickly and accurately than less familiar words, even in situations where they do know the words (i.e., the words are not completely unfamiliar). So, for example, a word like *head* is often rated as highly familiar as defined by the participant as both recognizing the word and knowing the meaning. A less familiar word, like *duct*, is one that the participant recognizes but is not confident they know the meaning. A word like *nave* may be rated as being even less familiar, with many participants not necessarily even recognizing the word and reporting not knowing the meaning at all. These measures of familiarity can be quantified directly, and familiarity measures are strong predictors of performance in a variety of speech perception tasks (e.g., Colombo et al., 2006). Usually, work in speech and language processing skirts this issue by only including words that are in the high familiarity category as stimuli (e.g., Bradlow and Pisoni, 1999).

Similarly, how frequently a listener encounters a word also significantly impacts perception of those words. For example, high frequent words, like *people*, are recognized more quickly and accurately than less frequent words like *hungry*; however, both words are roughly equal in their familiarity (Wilson, 1988; Brysbaert and New, 2009). That is, the frequency of use and familiarity of a word can be decoupled. This suggests that although both frequency and familiarity may impact speech perception, they are not the same construct and may impact speech perception differently.

In the case of medically related terminology, the effects of word (i.e., lexical) frequency and familiarity are quite pronounced. In one study, participants were asked to write down the words and sentences they heard in a variety of listening conditions (Bent et al., 2021). Listeners were exposed to sentences composed of medically related terminology in one of three categories. The medically related words were either high familiarity and high lexical frequency (e.g., *delivery, process*), high familiarity but low lexical frequency (e.g., *ulcer, toxic*), or low familiarity and low lexical frequency (e.g., *ectopic, tympanic*). Listeners were most accurate at writing down these sentences when listening to the high-familiarity, high-frequency words and least accurate for the low-familiarity, low-frequency words. However, this effect was even more pronounced in noisy conditions, including hospital noise. Although listeners perceive all speech less well in noise, the effect was particularly strong for less familiar words and especially for those words that are both less familiar and less frequent.

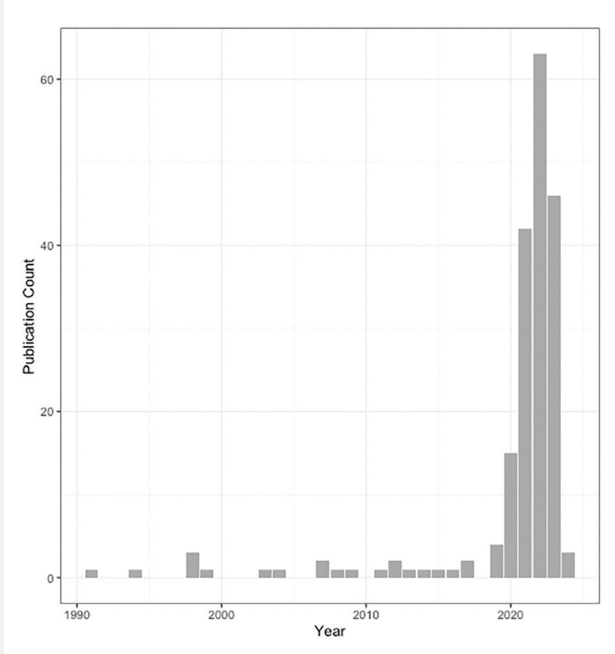


Figure 2. *Histogram of articles in speech perception and speech production through face masks from 1991 to 2024 (data from the Web of Science). Note the peak of publications in 2021, the year after the Covid-19 pandemic began.*

Speech Through Masks

During the Covid-19 crisis, there was a large influx of research investigating the perceptual challenges of speech perception when listening to an individual wearing a face mask. **Figure 2** shows that the number of papers published in 2020 examining speech perception and speech production with face masks was equivalent to the combined number of papers on the topic in the previous 11 years. In 2021, the number of papers on the topic tripled from the already high number in 2020.

Although masks are now much more ubiquitous than they were before the crisis, they have always been more prevalent in medical than in other settings, meaning that listeners are more likely to encounter a provider wearing a mask in these situations.

The challenges of speech perception through a mask have several sources. Masks can impact the acoustic properties of speech. Indeed, speech from health care providers who wear a mask shows a variety of reduced acoustic properties that may impact speech perception (McKenna et al., 2022). For example, the vowel articulation index (VAI), a measure that captures how distinct vowels are from one another in speech, is significantly reduced in speech through masks. Additionally, high-frequency (i.e., >4-kHz) information in the signal is also reduced. Interestingly, it is possible that these two effects are driven by different aspects of mask wearing. The reduction in high-frequency information may be due to filtering the effects of masks. However, the reduction in VAI is thought to be due to restrictions in jaw and lip movement when wearing a mask. Thus, it is possible that the mask not only creates a filter effect that impacts acoustic information but also that the act of wearing a mask can impact the articulation of speech and thus the acoustic characteristics of that speech.

Furthermore, listeners lose an additional channel of information during speech perception in the form of the visual information provided by a speaker's mouth movements. Although speech perception is often thought of as an auditory experience, it is, in fact, usually a multimodal one. That is, listeners incorporate visual information with auditory information when listening to speech (Rosenblum, 2008). Visual information is especially important in challenging listening situations such as noisy environments or listening to unfamiliar accents. It is also important for listeners, including older adults, who may have some hearing loss.

This information is disrupted with most face masks. One typical task used in speech perception work measures "intelligibility," or an individual's ability to write down the words or sentences they hear. This task can be done with video files that combine auditory and visual information or files with only auditory information. Recent work has demonstrated that intelligibility in an audiovisual task suffers a significant drop when the speaker is wearing a mask (see tinyurl.com/3wmcn484 for a discussion). This is true even when the mask is transparent and a listener could see some portions of a speaker's mouth (Brown et al., 2021). Interestingly, when listening to masked speech in an "audio-only" listening condition, this detriment to speech perception still exists. This finding suggests that some challenges in speech perception of masked speech are related to the filtering properties of the masks in addition to the challenges of lost visual information (Mendel et al., 2022). Moreover, challenges of listening to speech produced through face masks are greater in noisy situations (Toscano and Toscano, 2021) and when listening to nonnative speech (Smiljanic et al., 2021). Previous research has demonstrated that speech is easier to understand when speakers are explicitly asked to speak clearly compared with when they are speaking in a more conversational fashion (Bradlow, 2002). Speech produced through a face mask is even more challenging to understand when it is also produced conversationally compared with speech with intentional clarity (Smiljanic et al., 2021).

Cognitive Load and Listening Effort

Another aspect of medical interactions is that they can result in high levels of stress and anxiety. This issue is well-documented in cases of the "white coat effect" or "white coat hypertension," where anxiety about being in a medical situation results in physical symptoms, like increased blood pressure.

Similarly, anxiety impacts speech perception. Individuals who are acutely anxious perform poorly on speech perception tasks. In fact, this performance decrement is like participants completing other complex tasks that reduce performance. For example, a divided attention task where participants are asked to simultaneously do a speech perception task and another task such as a visual search. In such situations, participants do poorer in speech perception than when they do that task alone. When participants complete speech perception tasks during conditions designed to induce acute anxiety, a similar decrease in performance is seen even though there is no such competing task (Mattys et al., 2013). For example, when participants are placed in a situation where they are breathing in air enriched with 7.5% CO_2, a well-established mechanism to induce anxiety (Bailey et al., 2005), they perform poorly on a speech perception task compared with when they breathe normal air.

Stressful situations can also increase the listening effort required to understand speech. The listening effort is measured both subjectively and objectively using behavioral and physiological measures and has been shown to increase in a variety of challenging communication settings such as speech in noise or listening to an unfamiliar accent. Although an increased listening effort can result in improved understanding of individual words, an increased listening effort is also associated with costs later in processing. For example, a listener may suffer reduced comprehension and/or memory for content.

Listeners also demonstrate an increased listening effort (both subjective and objective) when listening to speech produced with masks. An increased listening effort can result in challenges not only with speech perception but also with poorer performance on secondary tasks and poorer memory for the speech the listener hears (Peelle, 2018). Indeed, memory suffers when listening to masked speech (Truong and Weber, 2021).

Listener and Talker Demographics

The issues described in **Speech Perception Challenges** exist regardless of the language background of the provider or the patient or the age of the patient. However, listener and talker demographics impact the efficacy of medical communication. As individuals age, they are more likely to interact with medical providers. Simultaneously, they are also more likely to face challenges in terms of both hearing loss and cognitive decline. Significant previous work has demonstrated that older adults have more difficulty than younger adults in a variety of challenging listening situations (Peelle and Wingfield, 2022). This difficulty correlates with both hearing impairments and cognitive impairments that occur as an individual ages.

Additionally, challenges in speech perception can be exacerbated when conversation partners do not share a language background. Graduates of international medical schools make up 40% of general medicine providers in the United States (Mick et al., 2000), suggesting that many medical providers have a first language other than American English and may speak English with an accent that may not be familiar to their patients. This could result in increased challenges for communication because listeners who have English as their first language often have more difficulty understanding speakers who learned English as adults than they do in understanding other individuals who share their first language. Furthermore, communicative efficiency between individuals who do not share a language background is reduced compared with those who do (Van Engen et al., 2010).

It is possible that international physicians are serving patients who are also second-language English speakers, which may reduce these challenges (see, e.g., Bent and Bradlow, 2003). However, this possibility seems unlikely as physicians from international backgrounds are most likely to practice in rural and underserved areas where patients are more likely to be first-language English speakers (Ranasinghe, 2015). One could imagine that similar challenges could emerge even for providers and patients who come from the same language background but are from different regions with different accents.

This linguistic challenge is representative of broader cross-cultural communication issues that may arise. Consensus in the medical field in the United States suggests that cross-cultural communication challenges not only exist (e.g., Powell Sears, 2012) but also can result in patient dissatisfaction and poorer health outcomes (Flores, 2000). Although the role of language, specifically, has been understudied, a 2021 meta-analysis suggests that matching language backgrounds with providers and patients correlate with increased compliance, patient satisfaction with their care, and improved clinical outcomes (Hsueh et al., 2021).

Other Challenges

Vocal Health and Vocal Strain

In most situations, medical providers must communicate verbally with their patients. Because individuals who are typically required to use their voices to conduct their jobs, medical providers are at higher risk for vocal problems than those who do not need to communicate verbally to conduct their jobs. For example, medical providers are more likely to face vocal strain and physiological challenges associated with this strain than individuals who are not required to communicate verbally in their job. Challenges of vocal problems may be exacerbated because the providers are often communicating in noisy situations, resulting in the Lombard effect (Lombard, 1911), a well-studied, involuntary response where a speaker speaks more loudly when in a noisy environment. This involuntary response would result in increased vocal effort in louder environments.

Issues of increased vocal effort are even more extreme when a health care provider is wearing a mask to communicate because individuals wearing face masks typically produce greater vocal effort than without a mask (Shekaraiah and Suresh, 2021). Effort can be measured both subjectively by asking a participant to rate how much effort they expended and objectively by measuring voice acoustics before and after speaking. Indeed, a study that investigated effort before and after the providers' workday demonstrated both increased effort and increased symptoms of vocal strain after a workday compared with before the workday began (McKenna et al., 2023). Symptoms of vocal strain may include hoarseness, loss of voice, and pain (Sandage et al., 2022). The potential implications on the vocal health of the provider and their well-being are concerning, given that vocal communication is a crucial piece of the work for many medical care providers, and increased vocal strain may be correlated with declines in the general well-being for providers.

Provider-Provider Interactions

The bulk of the work reviewed here has focused on medical provider-patient interactions because these are a core component of medical care and positive health care outcomes. However, it should be said that the issues raised in **Speech Perception Challenges** are likely to also hold for other types of interactions, including interactions between providers. Indeed, interactions between providers are paramount to patient safety and the essential function of health care settings. For example, during shift changes at a hospital, the doctor who is concluding their shift must convey information about their patients to the doctor who is beginning their shift. This might include information about dosage of medicine, state of symptoms, or new diagnoses. Although the patient's chart may contain some of this information, it is common practice for doctors to provide information to one another verbally during this "handoff."

Understanding the factors that impact communication between providers is quite important. A substantial body of work has demonstrated that individuals frequently and systematically overestimate the understanding of their interlocutors. That is, when asked to estimate how well a listener understood them, speakers believe that the listener understood more than they did (Keysar and Henly, 2002). Furthermore, this overestimation happens even when a speaker knows that the listener has a very limited ability to understand them. For example, when Mandarin Chinese speakers explained something in Mandarin to English-speaking Americans, they overestimated how much the listeners understood, even when explicitly informed that the listener did not speak Chinese (Lau et al., 2022). Crucially, such illusions exist in the medical field. When investigating the hand-off between two providers, providers systematically overestimated the effectiveness of their communication. That is, they believed that the hand-off was successful, even when they failed to communicate or understand the most critical information about a patient 40% of the time (Chang et al., 2010).

Calls for More Research

Despite the clear challenges facing many individuals listening to or producing speech in medical settings, this area of research is quite understudied. Although we understand many issues that may impact speech, most of the work in these areas is not done in situ using naturalistic noise or situations and most does not use realistic communication scenarios. Therefore, we call for more research in medical communication broadly speaking as well as in speech perception and production in these settings. It is our hope that through an influx of research in this area, we can provide recommendations to providers and patients to improve communication and overall health outcomes.

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Autism and Indoor Sounds

Fernanda Caldas, Samuel Underwood, Bruno S. Masiero, and Lily M. Wang

Loud music. Hunger. Metallic clattering from the kitchen. Strong smells. Bright lights. Conversations reverberate into a discordant blur.

> "Restaurants can be a triggering place for me. Not only do I have to maintain a conversation with the attendants, but I also must deal with the stress of these stimuli. At my favorite Mexican American restaurant, unlike many others where customers only state their order once, we're required to verbally select ingredients at each step, which can be particularly demanding for someone with a disability in communication and interaction. To accommodate customers with hearing or speech disabilities, this restaurant offers an alternative communication method: an order form. Although I do not explicitly fit these criteria, lowering my interaction demands in this adverse environment would benefit me. But do I have the right to use the form? Will attendants question my difficulties if they see me speaking and hearing?
>
> "After this experience, I started to hyperfixate on how I could benefit from proper indoor acoustics and noise control. Could this be a starting point for me to research architectural accessibility for autistic individuals? Surprisingly, it could" (F. Caldas, personal communication).

Such situations, as described by F. Caldas, emphasize the importance of acoustic accessibility in public spaces. Navigating the sensory overload encountered in daily life can pose unique challenges for autistic individuals. In this article, we describe autism and how autistic individuals experience the world of sounds. We then discuss the impact of indoor acoustics on autistic learners and highlight modifications that can improve acoustic accessibility in buildings.

Introduction

What is autism? The answer could depend on who you ask. Indeed, experiences and biases can lead different people to describe autism in different ways. Definitions of autism can, therefore, vary between health professionals, family members, school staff, allies, individuals who are not familiar with autism, and autistic individuals themselves. With time, society may converge toward a universal, neutral definition. For now, however, we, the authors, prefer the following definition: autism is a neurodevelopmental disability that impacts how individuals interact with the world, encompassing sensory experiences, communication patterns, and social behaviors as well as cognitive and motor skills.

Previous research has tried to understand autism by examining its traits, origins, and treatments and pursuing a cure. Unfortunately, studying autism alone can sometimes lead to the perception that autistic individuals are a problem due to their neurological characteristics. Instead, it is also necessary to consider how the environment and nonautistic (also called allistic) individuals interact with autistic persons. As authors, we view disability under the social model where disability is not an individual problem. Instead, it is society's responsibility to reduce the disabling experiences of persons with certain conditions (Oliver, 1990). In recent decades, the understanding of autism has developed to include other external aspects, such as the perception and characteristics of allistic persons, accessibility tools, inclusive education, and the effects of architectural design.

It is not uncommon to hear stories of autistic individuals disclosing their diagnosis publicly. In fact, the increasing number of newly diagnosed autistic adults has been highlighted in different scientific fields, including acoustics. One of the things that makes autism acoustically intriguing is the different auditory experiences

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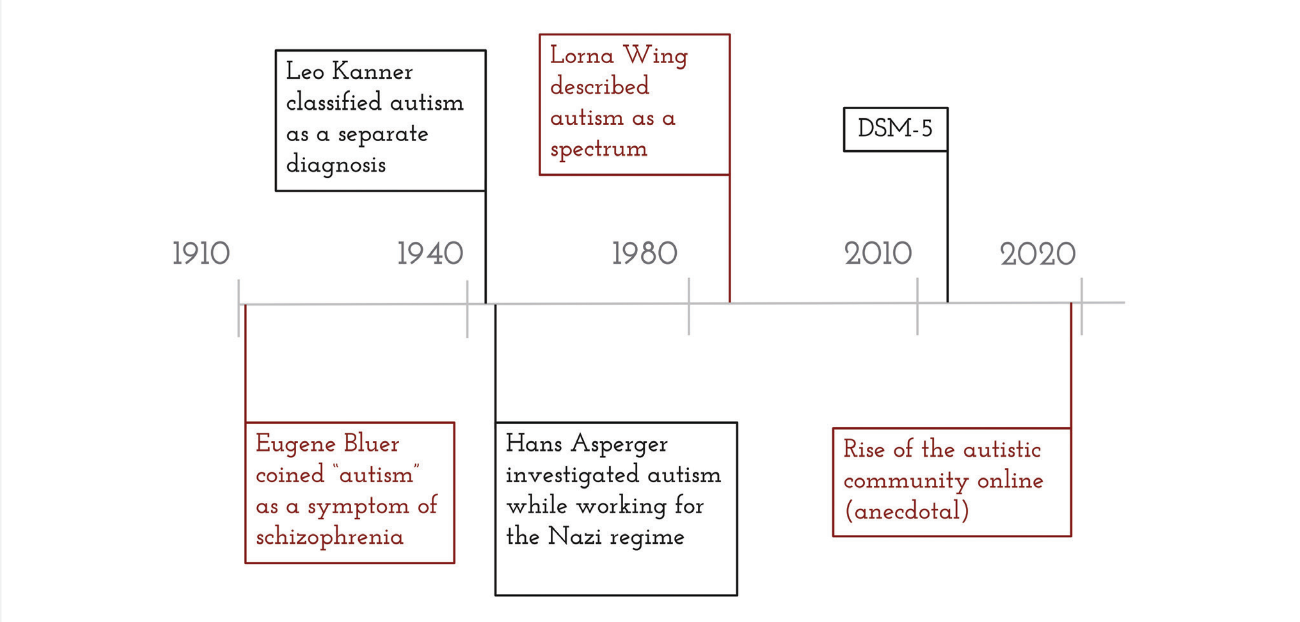


Figure 1. *Highlight of key events in the history of autism diagnosis. DSM-5,* Diagnostic and Statistical Manual of Mental Disorders-5.

reported by neurodivergent individuals (umbrella term for neurological conditions such as autism, attention deficit hyperactivity disorder [ADHD], dyslexia, dyscalculia, and dyspraxia) compared with neurotypical (i.e., nonneurodivergent) individuals. For example, neurodivergent people may perceive sounds as overwhelmingly loud or intense, struggle to filter out background noise, and/or experience discomfort or pain from everyday sounds. Consequently, they will often seek solitude or quiet spaces for relief.

Before diving further into the relationship between the built environment and autistic individuals, we consider the developments related to autism that occurred over the last century. A timeline is presented in **Figure 1**.

History of Autism

The word "autism" was first coined in 1911 by Swiss psychiatrist Eugene Bleuer as a symptom of schizophrenia in children (**Figure 1**). Bleuer coined the term from the word *autós* (meaning "oneself" in Greek) to describe children who became trapped in their own world of hallucinations to avoid contact with the outside world (Evans, 2013). In 1943, the Austrian American psychiatrist Leo Kanner used the term "autistic disturbances of affective contact" to establish autism as a separate diagnosis from schizophrenia. Kanner observed children who "have come into the world with an innate inability to form the usual, biologically provided contact with people" (Kanner, 1943, p. 250). Autism is, therefore, a relatively new diagnosis.

Hans Asperger, a German psychiatrist, also studied autism in the 1940s. Asperger analyzed autistic children who, according to him, exhibited potential for productivity, superior intelligence, and special abilities compared with the average population (Maher, 2021). He distinguished this set of characteristics as a "favorable side" of autism, which existed in some autistic children. Asperger also assumed the presence of genetic components, noting the recurrence of similar traits among family members (discussed in Hippler and Klicpera, 2003) as well as differences in sensory experience (e.g., hypersensitivity) compared with nonautistic children (Blakemore et al., 2006). Although this work may seem positive, Asperger's evaluations were used to separate children perceived as having potential from those deemed expendable (Czech, 2018) under the Nazi regime. Although not a registered member of the Nazi party, Asperger did cooperate with the regime and joined Nazi-affiliated organizations. There is disagreement in the literature regarding the extent to which Asperger was aware that his evaluations were used in the children's euthanasia program.

The societal and scientific view of autism shifted toward the end of the twentieth century, in large part due to the work of psychiatrist Lorna Wing at the Institute of Psychiatry, London, United Kingdom. As a parent of an autistic person, Wing (1988) described autism as a "continuum," or what is now commonly called a spectrum. This conceptualization highlights the set of characteristics that vary in intensity across different autistic individuals. Wing foresaw that this would facilitate the identification of more individuals on the autism spectrum. Consequently, Wing believed that this would empower a deeper understanding among previously undiagnosed individuals, which might lead them to improve the quality of their lives. Alongside Judith Gold, Wing developed what is now known as "Wing's triad," delineating three key diagnostic criteria for autism: deficits in social interaction, communication, and imaginative capacity (Wing, 1988). Wing also described autism as a lifelong condition (Silberman, 2015).

Diversity in the continuum of characteristics within the autistic community is now largely celebrated. In fact, the autistic community has cultivated a vibrant online space to connect with one another and share anecdotal evidence of their experiences. Some autistic individuals may choose to express their knowledge and feelings through social media and discussion in online forums. Such expressions and shared information have proven invaluable to researchers and professionals directly involved with autistic individuals, offering insights that contribute to a more comprehensive understanding of autism.

Still, autism is a dynamic topic subject to ongoing medical and social evolution. Initial research viewed autism as a pathology, but, over time, the term "symptom" has given way to "traits" or "characteristics" (Botha et al., 2022). Similarly, previous research that focused heavily on autism in children has been supplemented by recent works that have expanded the consideration to autism in adults (Parsons, 2015; Robison, 2019). More work is needed in this area.

How Is Autism Formally Diagnosed?

Currently, the Diagnostic and Statistical Manual of Mental Disorders (DSM) is considered the standard reference for formal autism diagnosis in the United States. The DSM delineates a spectrum of characteristics under the autism spectrum disorder (ASD) (American Psychiatric Association, 2013). Despite serving as a foundational resource, medical professionals and researchers have the freedom to interpret the manual as they wish. In the case of medical professionals, a formal diagnosis depends on the physician's interpretation of how autism manifests in a patient. In some cases, this subjective evaluation is a barrier to formally diagnosing adults and, therefore, is one of the arguments in favor of self-diagnosis. This is a controversial topic in the autistic community that we do not discuss here (Sarrett, 2016).

Autism is a disability that is generally characterized by difficulty in communication and social interaction, repetitive behaviors, restricted interests, cognitive rigidity, dichotomous thinking (i.e., rarely seeing nuances or gray areas), and hyposensitivity or hypersensitivity (American Psychiatric Association, 2013). For a time, the differences in sensory experiences between autistic and nonautistic people were ignored, but the differences later became a significant feature in the diagnostic process (Robertson and Baron-Cohen, 2017). Today, the diagnosis is based on the analysis of behaviors and statements provided by the autistic person and/or people in their lives. Although genetic and external factors may contribute to autism, there are no common biological markers in all autistic people.

There is no cure for autism, but there are some therapies and environmental interventions that significantly improve an autistic person's quality of life. Because the autistic community is heterogeneous, it is important to apply these therapies and interventions according to the needs of the individual.

Often, autism is categorized into three different support levels: Level 1 requires support, Level 2 requires substantial support, and Level 3 requires very substantial support. The required level of support is determined according to the intensity of different aspects that manifest in the autistic person (see **Table 1**) (Rudy, 2024). The intensity of each one is subjectively evaluated by a physician to determine the level of support. The level of support an autistic person receives may vary throughout their life and depends on the tools that their environment provides for independence.

Communication skills are commonly viewed to be the primary factor for determining the necessary level of

Table 1. *Some characteristics that vary in intensity*

Aspect	Description
Executive dysfunction	Difficulty in managing time, planning, changing focus from one task to another, or following instructions. It directly impacts learning and maintaining a formal job.
Dependence on others	Requirement of help for daily activities such as maintaining personal hygiene, eating, drinking water, and taking transportation. It relates to executive dysfunction.
Cognitive rigidity	How the person is affected by changes, even if they seem small.
Susceptibility to shutdowns and/or meltdowns	Shutdown = "inertia": disconnection from the environment, reduced ability to communicate, or total lack of communication. Meltdown = explosive crises: disruptive behaviors or risk of harm (to self or to others). Both can be the result of sensory and/or social overload, changes, and frustrations.
Co-occurring conditions	Other neurodivergences, intellectual disability, depression, anxiety, bipolar disorder, or schizophrenia.
Communication skills	General limitation/absence of speech or verbal communication that may vary depending on the context. We make the distinction between "speech" and "verbal communication" because the latter could refer to any type of communication that involves words in a structure (language).

These characteristics are subjectively assessed by a physician to determine the level of support of an autistic person. Level 1 requires support; Level 2 requires substantial support; and Level 3 requires very substantial support.

support, but this is not always true. One example is the misconception that every nonspeaking autistic person requires Level 3 support. On the contrary, some individuals may exhibit low executive dysfunction (see definition in **Table 1**), and demonstrate independence in daily activities and effectively utilize augmentative and alternative communication (AAC). AAC describes a range of communication methods that expand beyond relying only on hearing and speaking. AAC, for example, may include writing, sign language, text-to-voice and voice-to-text converters, graphic symbols, pictograms, and emojis. Many use AAC without even realizing they are doing so.

Indeed, modern technologies like cell phones and tablets play a crucial role in facilitating AAC, breaking down communication barriers for individuals with various disabilities and promoting greater independence. A few examples provided by modern technologies include video editing apps that generate automatic subtitles, artificial voices that read a text, and specific AAC apps that use pictograms to create phrases. Clark (n.d.) presents some examples of AAC applications that can be helpful for nonverbal individuals.

As discussed in the **History of Autism**, the understanding of autism has undergone significant transformation over the years. Historical perspectives on autism often reflected societal biases toward anything deemed abnormal and were even influenced by the prevalent eugenics movement in the twentieth century. Indeed, even today, metrics used to assess the intelligence, communication, and social abilities of autistic individuals can be skewed by this history.

Sensory Sensitivity

Autistic individuals often experience either hypersensitivity or hyposensitivity, two distinct traits that greatly influence their interactions with the world. Hypersensitivity is characterized by an intensified response to various sensory inputs such as light, sound, taste, touch/texture, and/or smell compared with the response of individuals without hypersensitivity. This trait is often associated with heightened anxiety and avoidance in negative situations or constant sensory seeking in positive experiences (Green and Ben-Sasson, 2010). Conversely, hyposensitivity involves an "underresponsiveness" to sensory input, potentially leading to a need for amplified sensory stimuli like louder sounds or brighter lights.

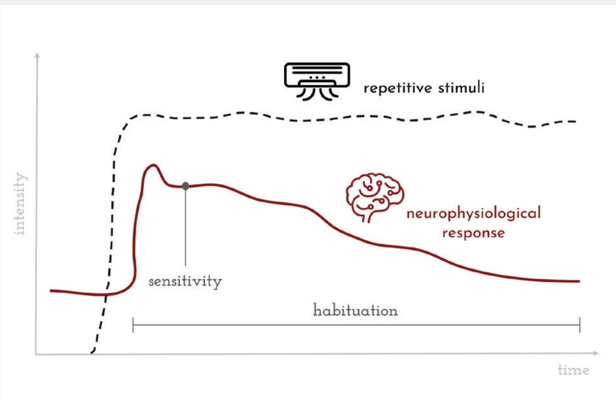
A recent study analyzed the sensitivity (immediate response) and the habituation (response to the same stimuli over a period of time) for autistic and neurotypical persons, with the aim of understanding how auditory hypersensitivity might function (Gandhi et al., 2021). It is usually expected that most people will become accustomed to constant background noises, such as the humming of an air conditioner. Consequently, we would expect an individual's neurophysiological response to decay over time as they become accustomed to the stimuli (see **Figure 2**). This is called habituation. Interestingly, Gandhi et al. (2021) showed that this habituation might not occur in autistic persons.

Measuring Sensory Responses

The galvanic skin response (GSR) is a reliable procedure used to analyze sensory responses in autistic individuals (Schupak et al., 2016). It assesses skin conductance, indicating physiological responses and elevated GSR levels, which serve as indicators of heightened emotional and/or sensory reactivity.

On the other hand, magnetoencephalography (MEG) gauges the electromagnetic activity of neurons and is used to track brain activity (Singh, 2014). GSR and MEG measurements of autistic and neurotypical individuals listening to tone bursts reveal that although the sensitivity does not differ between the two groups, habituation is considerably different. For example, neurotypical participants exhibited some level of habituation to a repetitive sound as their physiological response decreased over time. In contrast, autistic participants do not present a clear tendency for variation, but, on average, the physiological response stays approximately the same during the experiment.

Figure 2. *Simplified functioning of habituation. When exposed to repetitive stimuli (e.g., air conditioner), a person is expected to display a decaying neurophysiological response over time. Sensitivity is the response at an instant of time. Icon of the air conditioner is by ©keenicon via Canva.com. Icon of the brain is by ©satriyo pujo from Triyo Design via Canva.com.*



Thus, from the GSR measurements, one could infer that autistic participants are not habituating to such stimuli. The MEG results also indicated that neurotypical participants appeared to present some habituation, meaning that their neurological responses had a similar tendency and lower values over time. The autistic participants, however, did not present a common tendency within their group. No correlation between age and responses was observed in both groups (autistic and neurotypical) (Gandhi et al., 2021).

This work underscores an important conversation regarding strategies for accommodating autistic individuals in different environments. By continuously monitoring shifts in neurological and physiological arousal, it could be possible to preemptively identify and address possible physical and emotional discomfort through early interventions. This is particularly significant for individuals who require higher communication support, such as nonverbal or nonspeaking/minimally speaking autistic individuals. Still, these continuous monitoring methods need to be further investigated before they can be implemented. This research stands out for including both young adults and children, addressing a gap where most studies have focused on autistic children. Hopefully, more work detailing the experiences of autistic adults will emerge soon.

Finding Relief

Autistic individuals with auditory hypersensitivity can find relief using personal devices such as noise-canceling headphones and stim toys, including items like slime, fidget spinners, bubble pop toys, and chew necklaces (see **Figure 3**). In response to sensory overload or stress, a person might exhibit repetitive movements to achieve a sense of emotional regulation, which is often referred to as self-stimulatory (i.e. stimming) behavior. Stim toys help by channeling this type of reaction into a more controlled and less intrusive outlet, mitigating potentially harmful behaviors. Stimming is a valid form of self-expression that can also appear in joyful situations and, if it is not causing any harm, is not something to be corrected or avoided.

As mentioned in the **History of Autism**, social media can serve as an outlet for autistic persons to share their thoughts and experiences with an online community. In a recent post on Instagram, content creator and

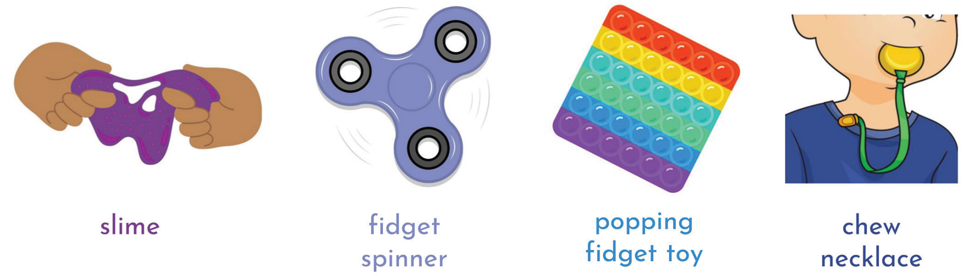


Figure 3. *Examples of stim toys.* ***Left to right***: *slime (©InstaStudio via Canva.com), fidget spinner (©igorkrasnoselskyi via Canva.com), popping fidget toy (©diluck via Canva.com), and chew necklace (©BNPDesignStudio via Canva.com).*

researcher Louise Chandler (2023) commented on her experience with reduced auditory habituation and her coping mechanisms as an autistic person. Among her coping mechanisms, Chandler highlighted the use of noise-canceling headphones and stim toys. Once she overcame her fear of judgment from others, Chandler found relief in accessibility aids, especially in situations of discomfort due to sound stimuli. According to Chandler, the sensitivity of autistic persons to sounds is often seen as a phobia rather than pain; therefore, it is something to "be overcome." However, repetitive exposure to such stimuli can increase their stress response.

Auditory Processing Disorder

Another characteristic linked to autism is the auditory processing disorder (APD) (Ocak et al., 2018). APD is, essentially, hearing a sound but not understanding it. The physiological parts of the auditory system are functioning, but the brain may not properly process what is being heard. A person with APD may face barriers to understanding oral instructions, lectures, movies, or TV shows without subtitles, and/or other forms of communication that rely heavily on the auditory system. APD makes it even more difficult to deal with noisy spaces, especially when there is a need to process speech, such as in a classroom. Although some persons with this characteristic may find it hard to understand speech, they may also easily identify instruments in a song (Berke, 2024). Thus, APD describes a range of auditory challenges that may vary from person to person.

Acoustics of Built Environments and Impact on Occupants

The built environment can directly influence the comfort, productivity, and health of its occupants, and acoustics is a key factor in this regard (Altomonte et al., 2020). Despite the recognized importance, guidance on acoustical considerations in the built environment remains less prevalent in building design and code requirements compared with other factors like thermal conditions, indoor air quality, lighting, or electrical systems. An exception to this trend is in the classroom where acoustical guidelines are often explicitly outlined, given their importance toward speech communication (Brill et al., 2018).

Lower signal-to-noise ratio (SNR) conditions correlate with worse speech intelligibility, student performance, and academic achievement as well as a greater listening effort (see references in Wang and Brill, 2021). Studies have also demonstrated that the negative effects of noise are worse for children than for adults, for those with hearing disabilities, and for those who are listening to nonnative-language speakers or who are nonnative listeners.

There are standards and codes that pertain to classroom acoustics. ANSI/ASA S12.60 (2010) established performance guidelines for background noise levels (BNLs) and reverberation time (RT) in unoccupied classrooms. Similarly, Section 808 (Enhanced Acoustics for Classrooms) of the 2017 ICC A117.1 Accessible and Usable Buildings and Facilities Standard (International Code Council, 2017) was recently adapted into the 2021 version of the International Building Code.

There are also examples of standards and codes that pertain to accessibility for individuals with disabilities. The Americans with Disabilities Act (ADA) in the United States, Federal Law Number 10.098 in Brazil, and Approved Document M in England and Wales, United Kingdom, are examples of such regulations. They primarily focus on architectural elements, detailing specific standards for individuals with physical disabilities. These include access to building interiors, dimensions of elevators and ramps, and methods to reduce physical obstacles. However, it is worth noting that regulations regarding indoor acoustics for autistic individuals are not yet widely addressed.

Impact of Acoustical Conditions on Autistic Children in Schools

Kanakri et al. (2017a) examined teachers' viewpoints regarding the academic progress and emotional and behavioral management of their autistic students across various educational levels, spanning students from preschool to high school in a variety of different subjects and settings.

The objective was to assess how noisy classroom environments affect autistic children and whether such conditions contribute to disruptive behavior. Teachers reported their opinions about specific sources of noise that are common in a learning environment. Air-conditioning and echoes were evaluated as having the most negative impact on autistic learners.

Teachers were also asked to name positive and negative acoustic characteristics of school environments. Positive aspects noted in classrooms included spaciousness and separation of different sensory zones with interconnected transition spaces. Metal furniture, echoes, hard floors, and a lack of carpet were reported as negative aspects.

The same research group observed that increased sound levels correlated with the appearance of repetitive behaviors such as repetitive motor movements, repetitive speech/echolalia, ear covering, hitting, loud sounds, and complaining in autistic children (Kanakri et al., 2017b). As mentioned in **Finding Relief**, repetitive behaviors in autistic persons may be indicative of distress. Still, the author emphasized the need for further tests of causal associations in a well-controlled environment. Other sources of discomfort need to be considered, such as social demands.

Impact of Acoustical Conditions on Autistic Adults in Learning Spaces

Rosas-Pérez et al. (2023) examined challenges and strategies related to acoustic conditions in various settings, focusing on perspectives of both formally diagnosed and self-diagnosed autistic adults. Through their responses, participants shared positive and negative experiences about home, work, and indoor/outdoor spaces. Notably, due to the prominence of educational contexts in responses, the study concentrated specifically on schools and universities from the perspectives of students and teachers.

Schools were characterized as "sensory hells," where auditory stimuli, bright lights, and smells were sources of distraction and discomfort. In addition to the discomfort caused by the noise itself, the unpredictability of the stimuli was also identified as an issue. Sensory overload in such environments was reported to lead to fatigue and hindered learning or teaching capabilities. Some participants faced challenges progressing through a university due to inadequate grades or similar difficulties. Those unaware of their autism were sometimes discouraged from acknowledging their difficulties, yet they still felt distinct from their peers and were accused of exaggeration. Knowledge of one's autistic status emerges as a possible way to understand and mitigate stressful situations.

Much has been said in the literature about the overall experience of children in schools, but there is little reported about the experience of autistic teachers. Indeed, insights gleaned from the experiences of

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autistic educators can inform the creation of more accessible spaces for children and adults alike. Rosas-Pérez et al. (2023) found that reverberant rooms and open-plan school configurations were identified as inducing sensory overload in autistic teachers. None of the participants who worked as teachers in schools continued their careers, with noise being one of the determining factors in this decision. The number of years worked prior to departing their teaching roles was not reported. Some participants sought alternative roles in education as consultants or academics.

Modifications to the Built Environment

How can we design the acoustics of the built environment to be more inclusive for autistic people? Through a review of 24 studies that mentioned sound and autism, Black et al. (2022) concluded that the answer involves careful consideration of factors that affect noise levels, such as spatial layout, sound isolation, and reverberation.

First, the layout of the built environment must be thoughtfully planned. Mostafa (2014) developed the ASPECTSS™ framework, which describes key principles in autism-inclusive architectural design. Areas should be spatially sequenced in a logical and predictable manner. Easy-to-access escape spaces should be designed to provide overstimulated users with a neutral environment in which to recuperate. Activity areas should be compartmentalized according to their function and sensory qualities. Transitional spaces can be used to help users adjust their senses to new stimuli in different environments. Transitional, storage, and prefunction spaces can be used to buffer acoustically sensitive rooms from surrounding noise sources.

When considering sound isolation, it is important to ensure that spaces are effectively shielded from external noise sources. External walls (and their openings) must block the transmission of disruptive sounds from the exterior (e.g., traffic, machinery, rain, human activity). Windows are often the weakest link through which sound can leak, but this can be mitigated with multipane window construction with an appropriately airtight and resilient joint sealant. The Sound Transmission Class (STC) and Outdoor-Indoor Transmission Class (OITC) of cavity wall systems can be improved with added mass, resilient layers, and cavity absorption. Partitions should extend to their full height and be sealed to the structure of the roof deck or floor above. Penetrations through sound-isolating partitions should be avoided. Wherever penetrations are unavoidable, they should be packed with insulation and sealed with a resilient joint sealant to minimize the leakage of sound.

Noise levels within the built environment also need to be controlled, not only through sound isolation of nearby activities but also through careful mitigation of in-room noise from equipment, appliances, and building systems. Bathrooms and kitchens are a common concern, given the noise associated with heating, ventilation, air-conditioning (HVAC), and plumbing systems (Mostafa, 2010). Kanakri et al. (2017b) suggested that the average sound levels should be kept at 50 dB or lower to reduce repetitive speech and hitting behavior in children. In some spaces, absorptive finishes, such as carpet, acoustical panels, and ceiling tiles, can be used to reduce the reverberation time and noise level.

These findings are supported by participatory research efforts, which seek to include the perspectives of autistic persons in the design process. For example, McAllister and Sloan (2016) developed a jigsaw activity for students aged 13 to 18 in which they conveyed their likes and dislikes by designing their ideal school layout. Noise was a common concern. Indeed, students suggested layouts that grouped louder programming at a greater distance from their resource base while also providing quieter spaces nearby. Students also suggested eliminating the school bell with a quieter notification system.

Looking Ahead

The exploration of acoustic accessibility for autistic individuals reveals a complex landscape beyond mere hearing. Autistic auditory experiences are diverse and intricate, encompassing challenges such as hypersensitivity and varied responses. Recent research recognizes the correlation between sound levels and behaviors, emphasizing the necessity for acoustical adaptations to minimize potential distress. Reinforcing existing design guidelines, especially in educational settings, becomes vital for ensuring clear communication and minimizing disruptive noises that could affect academic performance. Furthermore, comprehensive architectural design guidelines that take into consideration the diverse sensory needs of neurodivergent populations are needed.

We believe it is important to incorporate the perspectives of neurodivergent individuals into the design process. The participatory research efforts and interviews provide firsthand insights into challenges faced in educational settings, offering valuable suggestions for modifications. This collaborative approach, grounded in empathy and understanding, is pivotal for creating truly inclusive environments that cater to the unique sensory needs of all individuals. In essence, acoustic accessibility for neurodivergent individuals requires a holistic understanding, thoughtful adaptations, and a collaborative design process that places value on lived experiences.

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Beyond Anti-Noise: Foundations and the Future of Active Sound Control

Jordan Cheer and Felix Langfeldt

Introduction

Active sound control has today been applied to many practical noise control challenges, with commercial applications including car engine and road noise control, propeller aircraft noise reduction and, of course, noise canceling headphones. Research and development into further utilization of the technology is also continuing in a variety of areas, notably including maritime applications, consumer goods, and the built environment. However, the historical pathway to this point of productivity has been long, with some interesting twists in the scientific understanding and in both the technology development and its uptake.

The active control of sound is based on the fundamental physical principle of how waves generated by two or more acoustic sources interfere to create a desired sound field distribution. The physical occurrence of interference between waves was established in the context of light by Young (1804), and we have probably all experienced the associated double-slit experiment (tinyurl.com/4zx3nfwt). This understanding was extended to sound waves by Lord Rayleigh (Strutt, 1878), who reported observing "places of silence" in the sound field generated by two electromagnetically excited tuning forks. Lord Rayleigh, however, repeatedly noted the practical challenges of realizing such interference patterns experimentally due to the need to carefully synchronize the multiple sources. This partially explains why almost a century passed before active sound control systems, which rely on carefully tuned destructive and constructive sound field interference to achieve various objectives ranging from spatial audio reproduction to acoustic cloaking (Cheer, 2016), became practically viable.

This article provides a brief tutorial on the physical basis of active sound control before providing a review of its historical development and key milestones. Finally, future potentials of active sound control that may have an influence on our everyday lives are discussed.

Physical Fundamentals of Active Sound Control

The fundamental basis for active sound control techniques is based on the superposition principle, which is a fundamental property of linear systems, that states that when two or more waves travel through the same space at the same time, the net response is the sum of the individual waves. Many everyday situations involving acoustics can be well approximated as linear systems and, therefore, follow the principle of superposition. For example, in your classic hi-fi stereo setup that uses two loudspeakers, the sound that we hear is given by the sum or superposition of the two pressures generated by each loudspeaker at each ear. In acoustics, sound pressure is measured relative to the stationary ambient pressure. This means that pressures that are larger than the ambient pressure correspond to positive sound pressures and pressures that are smaller than the ambient pressure correspond to negative sound pressures. Consequently, considering the stereo hi-fi application, two positive pressures produced at our ear would be superimposed to give an enhanced total sound pressure, whereas a positive pressure superimposed with a negative pressure would give a reduction in the total sound pressure level.

The concept of superposition is illustrated in **Figure 1**, where examples of the superposition for two sinusoidal signals are shown. **Figure 1**, *top*, is widely used to illustrate the principle of active noise control. It shows two sinusoidal signals with equal amplitude but opposite phase. Superimposing these two signals results in the primary signal being exactly canceled by the secondary signal, leading to a combined signal with a value of zero.

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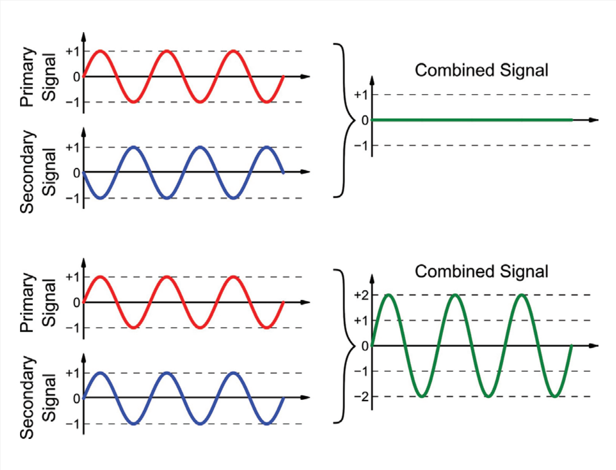


Figure 1. *Illustration of two basic superposition effects using sinusoidal wave signals.* ***Top:*** *sound cancellation using destructive interference.* ***Bottom:*** *sound enhancement using constructive interference.*

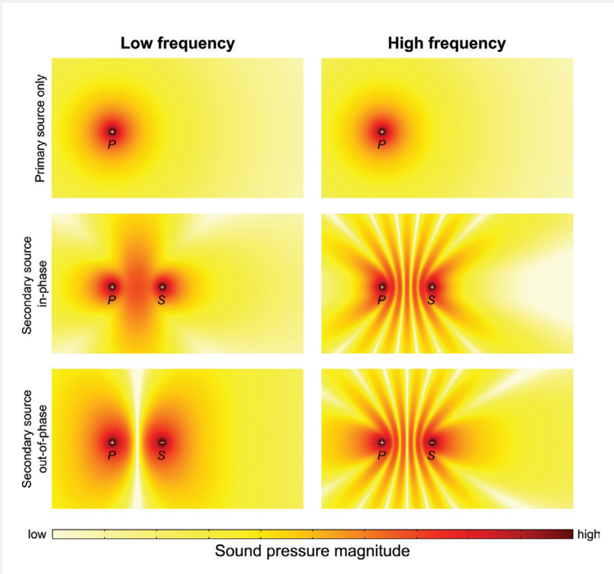
This process is commonly called "noise cancellation" and the term "anti-noise" is used to describe the secondary sound signal as being the "opposite" of the primary signal, although this perspective misses many details of practical active noise control system design. It is worth noting that this concept is not limited to sinusoidal signals but can, in principle, be extended to arbitrary primary signals (e.g., speech) as long as the secondary signal can be generated to exactly cancel the primary signal.

Figure 1, *bottom*, illustrates another fundamental consequence of the superposition principle, which is less often discussed in the context of active noise control but is relevant more broadly to active sound control. In this case, the two sinusoidal signals are in phase with each other, which results in constructive interference between the two signals and a doubling in the amplitude of the combined signal. This principle is utilized in various active sound control applications, including active sound equalization (Kuo and Ji, 1995), where active control may be used not only to attenuate unwanted noise but also to enhance wanted noise. For example, these techniques can be used to actively modify the acoustic characteristics of an internal combustion engine to make a low-power engine sound sportier (Samarasinghe et al., 2016).

The examples shown in **Figure 1** apply to interference mechanisms in both time and space. Thus, in active sound control, it is crucial to control the secondary signal both temporally and spatially. This means that actively controlling sound throughout a large volume of space becomes challenging.

Figure 2 illustrates this challenge for a spherical sound wave radiated by a monopole source (e.g., a loudspeaker) into free space. **Figure 2**, *top*, shows slices through the sound pressure field radiated by the primary source (P) at two different frequencies, with *dark red* corresponding to higher pressure amplitudes and *light yellow* representing lower sound pressure levels. In **Figure 2**, *middle*, a secondary source (S) has been added at a distance away from the primary source and is driven in phase with the primary source. This results in a complex interference pattern, with areas of low sound pressure level due to destructive interference and areas of enhanced sound pressure level due to constructive interference. As the frequency is increased and the wavelength becomes smaller, the complexity of the interference pattern also increases,

Figure 2. *Sound pressure radiated by a primary source (P) and a secondary source (S), modeled as monopole sources, into a three-dimensional free field at low and high frequency. The spacing between the sources equates to 0.7 of the acoustic wavelength at low frequencies and 3.5 times the acoustic wavelength at high frequencies.* ***Top:*** *the field is radiated by the primary source only.* ***Middle:*** *the secondary sound source radiates sound in phase with the primary source.* ***Bottom:*** *the secondary sound source is out of phase with the primary source.*



with more areas of both low and high sound pressure levels being produced.

These sound field interference patterns highlight two crucial challenges for active sound control in three-dimensional sound fields: First, the phase of the sound field radiated by a single secondary source cannot be controlled independently at different locations in space. This means that driving the secondary source with an out-of-phase signal to achieve cancellation at one location can lead to (possibly unwanted) sound enhancement at another location. Second, because the interference pattern depends on the frequency, a quiet zone at one frequency may correspond to a region of enhanced sound pressure level at another frequency, which complicates the tuning of the secondary source.

A common misconception in terms of active noise control is that to "cancel" sound, the secondary sound source needs to be driven out of phase with the primary source. This scenario is illustrated in **Figure 2**, *bottom*, which shows that when the primary and secondary sources are not collocated at the same point in space, cancellation throughout the space does not result from driving the two sources out of phase with each other. In fact, driving the secondary source out of phase simply leads to regions of cancellation and enhancement swapping positions compared with the case when the sources are in phase with each other.

In practical active sound control systems, the secondary source needs to be driven such that the desired pressure reduction or enhancement occurs at the required target location. In many practical cases, the primary source does not act at a point but is distributed over space and a single secondary source simply cannot generate the complex sound field required, especially in large volumes (such as rooms or aircraft cabins) and at higher frequencies. As a result, multiple secondary sources are used in practice to achieve the required degree of sound control over a wider spatial volume.

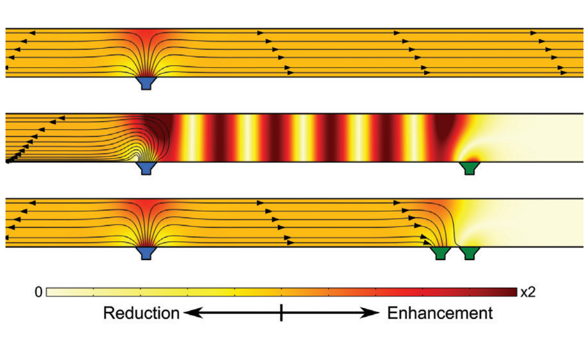
We now know that to actively control the sound radiated by a primary source, we need at least one secondary sound source that must be driven with a certain phase relationship with respect to the primary source to achieve the desired sound field. In the context of active noise control, this often raises the question about the energy balance in the system:

> "If a secondary sound source is introduced to reduce the sound pressure but this secondary sound source also introduces energy into the system via its radiated sound power, why is the total energy in the system not increased by the secondary source?"

To provide insight into this interesting question, **Figure 3** shows the pressure magnitude (*colormap*) and sound energy flow or acoustic intensity (*black streamlines*) for two different approaches to realizing active noise control in a duct. The first system (**Figure 3**, *top*) represents the duct with only the primary source radiating sound. The resulting pressure magnitude field in the duct is mostly uniform, indicating the propagation of plane waves (the pressure magnitude varies moderately in the vicinity of the primary source, which is a result of the near field). The sound energy flows along the duct in both directions away from the primary source, as one might intuitively expect.

In the second system (**Figure 3**, *middle*), a secondary sound source is introduced some distance away from the primary source. The secondary source is driven to achieve destructive interference and therefore noise cancellation to the right of the secondary source. The near-zero pressure magnitude field on the right of the secondary source clearly shows that this is achieved.

Figure 3. *The sound pressure magnitude (**colormap**) and steady-state flow of acoustic energy (**black streamlines and arrows**) in a duct due to a single primary source (**top**), active sound control using a single secondary source (**middle**), and active sound control using a pair of secondary sources (**bottom**).*



However, a specific pressure field pattern can be observed between the primary and secondary sound sources, which corresponds to the formation of a standing wave. The *colormap* in this region reveals that the pressure is doubled in certain places where the primary and secondary sound fields interfere constructively. This shows that even though it is possible to reduce the sound pressure in certain regions of the duct with a single secondary sound source, the pressure is increased at other locations. In terms of the energy flow, the streamlines in **Figure 3** indicate that the sound energy only travels to the left, with the standing wave field effectively operating as a barrier through which the sound radiated by the primary source cannot propagate. In this case, therefore, the energy is not reduced but is simply reflected by the action of the secondary source as if it were a rigid barrier.

To achieve full sound cancellation in the right half of the duct without introducing either a standing wave field or regions of increased sound pressure, it is necessary to introduce an additional secondary source as shown by the final system (**Figure 3**, *bottom*). The original secondary source is now driven to cancel the sound waves generated by both the primary and additional secondary sources to the right of the secondary sources. The additional secondary sound source is driven to cancel the sound radiated by the original secondary source to the left of the secondary sources. In this case, the pressure field to the right of the secondary sound sources is fully canceled, whereas the pressure field between the primary and secondary sound sources is now unchanged by control. The total acoustic energy in this system is clearly reduced, but where does the energy go? The streamlines reveal that the acoustic energy radiated by the primary source propagates away from the source in both directions, but the energy propagating toward the secondary sources then flows into the first secondary source and does not propagate further along the duct. This control strategy is typically called active absorption control because the secondary source absorbs the acoustic energy. The mechanism by which the energy is absorbed depends on the nature of the secondary source.

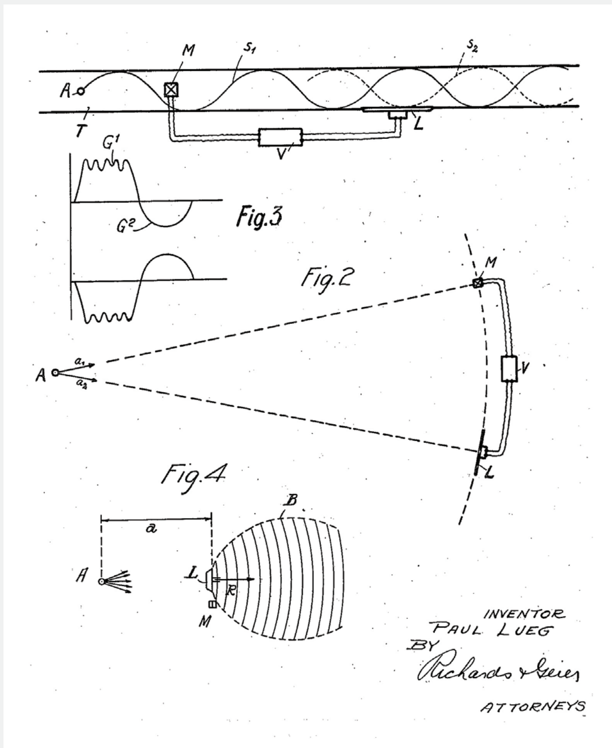
The physical fundamentals of active sound control discussed here briefly can be extended to more complex scenarios where it is necessary to bring together an understanding of the physical acoustics, the signal processing, and the control theory. The interested reader is referred to the many excellent textbooks on the subject including Nelson and Elliott (1991).

Historical Development and Milestones

Ideation

The invention of active noise control is often attributed to Lueg (1933), who filed a patent application in Germany (and subsequently in the United States [1934]) covering the concept of controlling noise in both one-dimensional and three-dimensional environments via destructive interference. However, a French patent, filed a matter of weeks previously by Coanda (1932), initially proposed the idea. The story behind Lueg and his seminal patent

Figure 4. *Diagrams from an early active noise control patent. M, a microphone; L, a loudspeaker; V, an electronic controller; A, the acoustic primary source. The* ***top*** *figure shows a potential duct active noise control realization. T, the duct; S_1 the primary sound wave; S_2, the secondary source wave. Fig. 2 shows a potential system for the control of spherical waves in a free-field environment. Fig. 3 depicts the meaning of phase opposition for nonsinusoidal signals, shown by the irregular curves G_1 and G_2. Fig. 4 shows an alternative free-field implementation where the secondary source is at a distance (a) from the primary source and where B is the zone of noise reduction that primarily occurs in direction R. Reproduced from Lueg (1934).*



has been nicely discussed in *The Journal of the Acoustical Society of America* by Guicking (1990) and the common mix-up in attribution of the invention is highlighted in a following comment by de Heering (1993).

Despite this interesting historical note, it is quite widely accepted that Lueg's patent (1933) provides the cornerstone of active noise control, with the diagrams page from the patent (Lueg, 1934) reproduced in **Figure 4**, proposing the first physically realizable mechanisms of achieving noise control via wave interference. In the top figure shown in **Figure 4**, Lueg proposes a means of achieving noise control in the duct application shown in **Figure 3** to introduce the physical basis of active noise control. This practical realization utilizes a microphone (M) to detect the unwanted primary wave (S_1) which is then manipulated by an electronic controller (V) and used to drive the loudspeaker (L), which generates the secondary wave, (S_2) that has equal amplitude and opposite phase to the primary wave (S_1). The two acoustic waves will thus interfere destructively and lead to a reduction in the noise level, as discussed in relation to **Figure 1**. In addition to the one-dimensional duct application, Lueg also presented concepts for the control of free-field sound in three-dimensional spaces ("Fig. 2" and "Fig. 4") and considered the control of sound waves that are nonsinusoidal in "Fig. 3."

Olson's Electronic Sound Absorber

Despite the clarity and insight provided by Lueg's patent (1933), a practical system was not demonstrated for another two decades due to limitations in the available electronic hardware at the time. A significant step forward, however, came via the work of Olson and May (1953), which demonstrated a practical method for realizing an active noise control system. The proposed system shown in **Figure 5,** like the conceptual systems in Lueg's patent (1933), utilized a microphone, amplifier, and loudspeaker. However, in the case of Olson and May's work (1953), the control system was based around tuning the feedback between the microphone and loudspeaker to generate a zone of noise cancellation around the microphone rather than achieving control via a feedforward approach using the prior knowledge of the unwanted primary noise provided by the "upstream" microphone in the duct system shown in **Figure 4**. In addition to the first practical demonstration of active noise control, perhaps the more impressive contribution from Olson and May (1953) was their foresight in the breadth of potential active noise control applications. A summary of the diagrams depicting potential applications is presented in **Figure 6.**

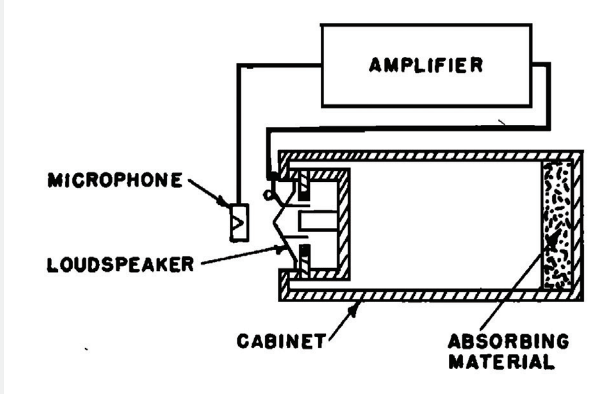


Figure 5. *The "electronic sound absorber" proposed by Olson and May (1953) in which a microphone signal is used to drive a loudspeaker after modification by an amplifier. The loudspeaker is enclosed in a cabinet with enclosed absorbing material. Reproduced from Olson and May (1953), with permission from the Acoustical Society of America.*

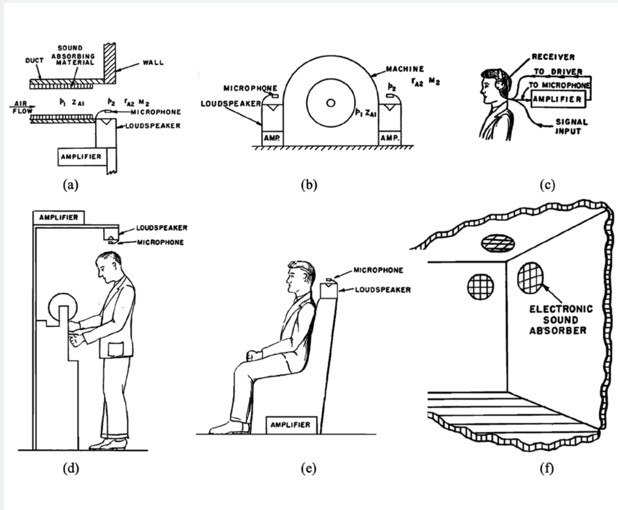


Figure 6. *A summary of the potential active noise control applications proposed by Olson and May (1953) and Olson (1956). Applications include control of noise radiation from ducts (**a**) and machinery (**b**); noise canceling headphones (**c**); active reduction of noise around the head of a machinery operator (**d**) or the occupant of a seat in an aircraft or automobile (**e**); and active control of the acoustic environment in a room (**f**). Reproduced from Olson and May (1953) and Olson (1956), with permission from the Acoustical Society of America.*

Fighting Noise with Noise

At a similar time to when Olson and May (1953) proposed their feedback active noise control system, Conover (1956) proposed a practical feedforward active noise control system for the reduction in the harmonic noise radiated by electrical mains power transformers (**Figure 7**). This system provided noise reduction in the order of 15 dB, but the performance was significantly degraded by changes in the transformer noise over time due to operational conditions and therefore required regular adjustment by the operator of the amplitude and phase to maintain control. Although Conover (1956) discusses a potential mechanism of automatically adjusting the control system, he notes that "development of an inexpensive system of this type would be quite a project," and this technological limitation largely stalled the development of active noise control systems once more.

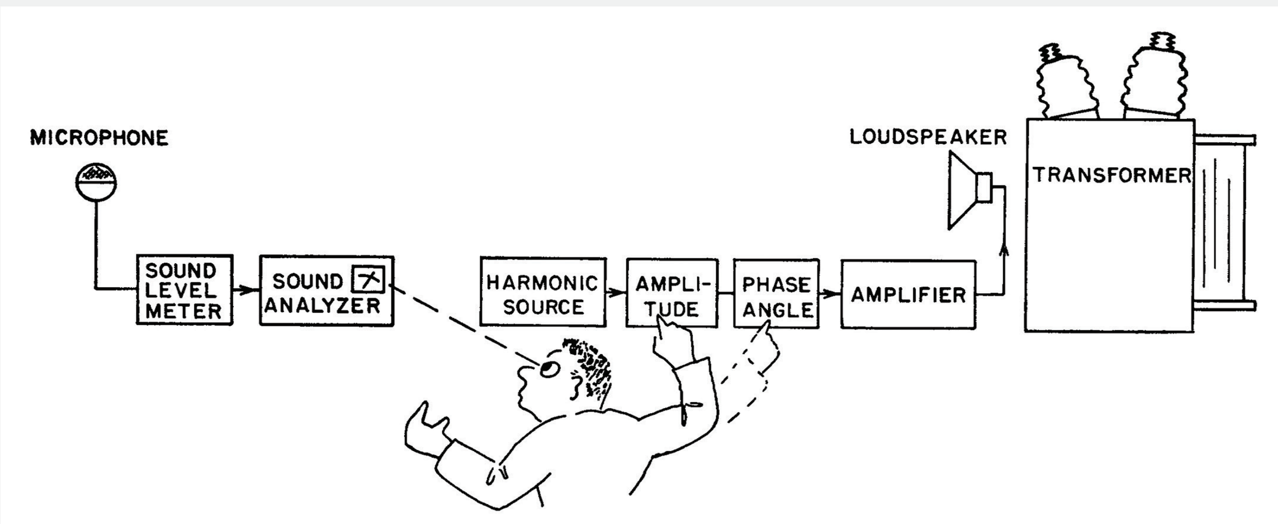
Advent of Digital Systems

The ability to automatically adjust the magnitude and phase in a tonal active noise control system became a practical reality with the emergence of digital signal-processing methods and systems in the 1970s. The first digital active noise control systems were reported in the work by Kido (1975) and Chaplin et al. (1978), the latter of whom proposed a digital waveform synthesizer to adaptively control the noise generated by the repetitive processes typical of many machinery noise problems. These early works spawned modern digital feedforward active control system design and, correspondingly, the number of academic publications has grown rapidly since this foundational work.

Despite the importance of this early work on the realization of digital active noise control systems, the most significant step forward came with the proposal of the Filtered-x Least-Mean-Square (FxLMS) algorithm for active noise control applications (Burgess, 1981) and its generalization to the minimization of multiple microphone signals (Elliott et al., 1987). This algorithm can effectively handle the real-world variations over time that require changes in the amplitude and phase of the control signals, as reported by Conover (1956) and referenced in **Figure 7**.

The FxLMS algorithm was derived from the adaptive noise canceler developed for the removal of additive noise from electrical signals (Widrow et al., 1975) but takes into account the phase shift due to the response between the secondary source and the microphone that, if ignored, would lead to an unstable system. The FxLMS algorithm has been widely studied and the interested reader is referred to Kuo and Morgan (1996) and Elliott

Figure 7. *Active noise control system for transformer noise reduction. The system uses a microphone and analysis system that the user monitors to manually adjust the amplitude and phase of a harmonic signal, with the same frequency as the transformer harmonic being controlled, which is then used to drive a loudspeaker. Reproduced from Conover (1956), with permission from the Acoustical Society of America.*



(2001) for a more complete introduction to the algorithm. Suffice it to say, however, despite the emergence of many other adaptive active noise control algorithms, the FxLMS algorithm has remained the most widely applied due to its robustness to real-world challenges and relative simplicity.

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In this *Across Acoustics* episode, we talk to a student author about his research regarding using 3D printing to create noise-attenuating structures that take up less space.

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Application and Exploitation

The advent of digital signal processing was the key technology trigger that enabled researchers to seriously explore the potential application of active noise control to real-world challenges. This resulted in a rapid growth in research, which was reflected by a sharp increase in published articles from around the late 1980s. Early application examples include engine noise in cars (Elliott et al., 1988), propeller aircraft noise (Elliott et al., 1990), rotor tone noise in helicopters (Boucher et al., 1996), road noise in cars (Sutton et al., 1994), and the exploration of noise canceling headsets particularly for pilot and military applications (Goodfellow, 1994). This period of active noise control research was extremely productive, providing advances in the areas of physical acoustics, signal processing and control and, significantly, understanding of how these various aspects of active noise control systems interact.

Despite the promise and many impressive practical demonstrations of active noise control systems in the late 1980s and early 1990s, widespread commercialization of the technology was not achieved. As noted at around that time by Elliott and Nelson (1993), this can perhaps be related to the technology being "somewhat oversold," with the result of a prevailing expectation that active noise control would be able to silence all noise problems.

Following the technology trigger associated with the availability of digital systems, the boom in research in the late 1980s and early 1990s coincided with a peak of inflated expectations. With inflated expectations, it is perhaps unsurprising that a period of disillusionment in the technology followed, with the technology not delivering what was perhaps misleadingly promised. However, active noise control technologies emerged from this period with active noise canceling headphones, as envisioned by Olson (1956) and shown in **Figure 6c**, moving from a high-cost industrial technology to a consumer product in 2000 (see tinyurl.com/2p96rfpe) and large-scale noise control systems being commercialized in passenger propeller aircraft by Ultra Electronics (Hinchliffe et al., 2002). Versions of these successful products are still in operation today, and by demonstrating the value of active noise control technologies when integrated effectively and applied to well-suited noise control challenges, they moved the technology into a period of enlightenment.

Once useful, functional, and cost-effective applications of active noise control began to emerge, with appropriate levels of expectation, the route for applications opened in a variety of areas. For example, in the automotive sector, although early systems demonstrated the feasibility of both engine and road noise control, excluding early production vehicle systems such as that installed briefly in the Nissan Bluebird (Hasegawa et al., 1992), utilization of active engine noise control only began to grow in the early 2000s (Sano et al., 2001) and became widespread around a decade later. Many automotive manufacturers now utilize active engine noise control, particularly in hybrid vehicles or vehicles with cylinder deactivation technology where active control enables a more consistent driving experience (Samarasinghe et al., 2016).

Although active engine noise control has now been in a period of productivity for some time, many other applications of active noise control stalled or have yet to reach this point. For example, active control of road noise has not yet quite reached this stage due to its more challenging nature. Some production vehicles with road noise control have been released, with the first production vehicles launched in 2020 by Hyundai using a Harman control system (see tinyurl.com/2swv2tk6) and by Land Rover using a Silentium system (see tinyurl.com/tz4k66e8). However, usage has yet to become mainstream. This may, however, change quite rapidly with the increasing market share taken by electric vehicles, whose acoustic environment is more strongly dominated by road noise.

Future Potentials

Many more applications of active sound control exist than can be discussed in this article, including in the marine sector (Daley et al., 2004) and built environment (Lam et al., 2021), with a spectrum of levels of technology maturation. It is interesting to note that like many technologies, active control has taken its time to reach widespread use. This was initially due to a lack of suitable supporting technology but then became a challenge of aligning expectations to realistic and often physically imposed performance limitations. The future of active control is certainly now generally within a period of productivity, with clear understanding of what can physically be achieved with active treatments. Applications are now typically focused appropriately and rather than utilizing active control as an add-on solution to fix a problem, it is increasingly being treated as part of an integrated design process with passive noise control treatments.

Due to a wider understanding and reducing costs, active sound control is increasingly being explored for more cost-sensitive applications, such as consumer goods including washing machines and dishwashers (Mazur et al., 2019). Additionally, with the explosion of interest and research into artificial intelligence, there is a growing collection of novel active sound control-based systems that provide new functionality, including situation-dependent behavior or a personalized experience.

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Listening to the Ocean Offers Insights into Climate Change

Lauren A. Freeman

Introduction

Oceanography classes teach that sound is to the sea what electromagnetic radiation, or light, is to the atmosphere. And, in fact, oceanographers and acousticians study the ocean environment using sound with a goal of understanding how new sources of sound may travel through the many layers of seawater that make up the ocean. To do this, they interpret noises of the environment that are picked up by hydrophones.

Indeed, acoustics offers a window into the undersea realm. The ocean's acoustic environment, also known as the ocean soundscape, incorporates sounds, or "signals," from humans, animals, plants, weather, the seafloor, and surface waves. Moreover, how ocean animals perceive and respond to these signals tells us a lot about the undersea environment. On short timescales, animals may change their behaviors to be quieter to avoid predators or to vocalize at the same time, cued by a full moon, to attract mates. On longer timescales of years, patterns in whale song or fish calls shift in response to the environment changing, in terms of both human use and climate change.

We know that many ocean environments are in a state of stress and flux due to ocean warming, ocean acidification, shifting weather patterns, and other effects of climate change (Garcia-Soto et al., 2021). Marine species have adapted to the historic specific ranges of temperature, salinity, and pH (e.g., Sanford, 2014; Costello et al., 2017). But now, these variables are no longer following their historic norms due to an excess of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere and ocean, and this has a potential impact on marine species. This can be a major problem for certain species, which can have cascading effects on ocean ecosystems. One way to understand and monitor what is happening in the maritime environment under this extreme stress is through the use of acoustics. In fact, acoustics may also inform human efforts at ecosystem conservation, mariculture, and carbon capture. Indeed, numerous studies on ocean soundscapes incorporate data from coral reefs to a wider range of environments including temperate reefs (Van Hoeck et al., 2020), kelp forests (Gottesman et al., 2020; Butler et al., 2021), deep reefs (Archer et al., 2018), and pelagic environments. This article focuses on the intersection of ocean soundscapes and climate change.

Ocean Soundscapes

The unique mixture of physical noise, biological noise, geologic noise, and anthropogenic noise in the sea comprise the soundscape (Cotter, 2008; International Organization for Standardization, 2017). Of importance, each marine ecosystem and environment has a unique soundscape that provides information about where one is in the world's oceans and estuaries, what the weather is above and below the surface, what plants and animals are passing through or are resident in that location, and how humans are utilizing that particular piece of the ocean. If we understand the soundscape, we understand the environment.

Soundscapes in the air are quantified relative to a human's perception of the acoustic environment, which incorporates sound sources and the ability of humans to detect these sources (Aletta et al., 2016). Soundscapes are often described in association with a place, such as a temperate forest in the spring, an aspen forest in Colorado in the fall, New York City's Fifth Avenue at rush hour, or an Irish pub in your town. Although none of those descriptions include any audio information or spectrograms, each description likely invoked ideas of particular sounds as you read them.

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Underwater, human perception of sound is less relevant than the sounds received at a hydrophone for humans to study later or the sounds received by ocean inhabitants. This is how underwater soundscapes are defined in a previous *Acoustics Today* article (Miksis-Olds et al., 2018) as "the sum of multiple sound sources that all arrive at the location of a receiving animal or acoustic recorder." The underwater soundscape will usually integrate sound sources over a much larger area than an in-air soundscape due to the nature of sound wave propagation through seawater. A hydrophone or marine animal could be receiving sound sources from thousands of kilometers away as well as from sources just a few meters away.

In underwater acoustics, the key distinction between ambient noise and underwater soundscapes is that ambient noise is all background noise that is not readily identifiable and soundscapes include all sounds in the environment (Cato, 2018). There is an ongoing discussion in the underwater acoustics community of incorporating perception by the listener into the definition of an underwater soundscape, particularly in the context of behavioral ecology and changes in species behavior under different soundscapes. Is perception simply the signal that can be received by a particular animal, which we calculate mathematically from both the ability of the sound source to travel through seawater to reach the auditory mechanism and physiologically from the nature of the auditory mechanism? Or do we go another step and include the response of marine animals to these auditory signals? The former is aligned with the in-air definition of a soundscape (Grinfeder et al., 2022, and references within). The latter focuses on the contribution of anthropogenic sound to marine environments, resulting in modification of behaviors of marine animals.

Soundscapes and Marine Life

Soundscape studies have revealed a wealth of information about ocean ecosystems. Fish calls and choruses continue to be discovered around the world, with many ocean ecosystems hosting a range of fish choruses, each with a different function (McWilliam et al., 2018). Individual fish calls tend to bedrums, purrs, and croaks ranging from 500 to 2,000 Hz. During spawning aggregations, fish vocalize in unison. In Golfo de Santa Clara, Mexico, for example, local fishermen have observed that the chorusing corvina (*Cilus gilberti*) are so loud underwater that they can be heard in air, quite the acoustic spectacle (Freeman, personal communication, 2013)! Along the mid-Atlantic Coast of the United States, the aptly named oyster toadfish (*Opsanus tau*) males call in a series of grunts and croaks called a "boatwhistle" to attract mates to its nest (Fine, 1978). Listen to an oyster toadfish call at bit.ly/Opsanus. On the other side of the world in the Indo-Pacific, frogfish (*Antennarius sp.,* commonly referred to as frogfish in the Northern hemisphere and anglerfish in Australia) have a similar ecological role (Myrberg, 1997). Both the oyster toadfish and frogfish look rather lumpy and odd (**Figure 1**), both are poisonous, and both vocalize loudly both to scare intruders away from their territory and to attract a mate. Indeed, fish calls are often associated with spawning or efforts to attract mates, with the oyster toadfish being just one particularly noisy example.

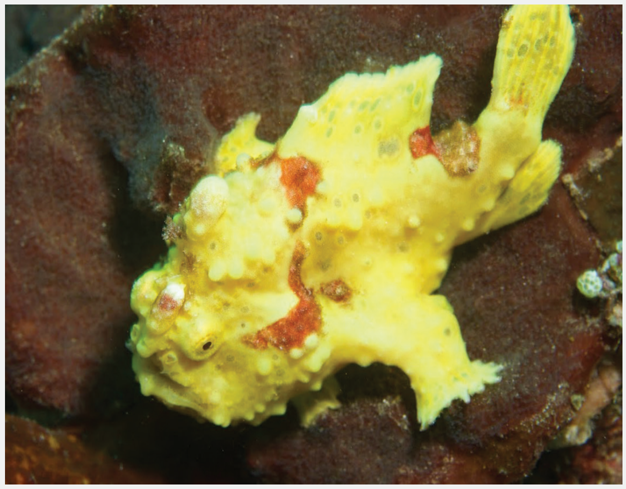

Figure 1. *The frogfish, like the toadfish (not shown), does not have a common fish shape nor does it swim well. Both are bottom dwellers that are poisonous snacks to their predators and discourage predation by vocalizing. In addition, the male fish of both species call loudly to encourage female mates to visit their nests. Photo by L. Freeman.*

The soundscape of a coral reef is akin to our own heartbeats, revealing the health and state of the ecosystem itself (Freeman and Freeman, 2016). A healthy reef has an acoustic signature that is rich in low-frequency sounds, including fish calls and invertebrate snaps, clicks, and pops (**Figure 2**). The Hawaiian damselfish (*Dascyllus albisella*) are small but incredibly noisy, acting like guard dogs barking at anything that gets too close to their nest. Many damselfishes in the family Pomacentridae are similarly noisy and

Figure 2. *A crab nestled inside live coral. This is a simple example but illustrates one of the primary sound production mechanisms by invertebrates on coral reefs. Invertebrates have hard shells or external skeletons. As they move about the hard surface of the coral reef, the shells hit the reef structure and click or snap, creating a portion of the background snap, click, and pop of invertebrate sound common to healthy coral reef soundscapes. Photo by L. Freeman.*

territorial in tropical and subtropical waters around the world. Listen to a dusky damselfish (*Stegastes fuscus*) call at bit.ly/DuskyDamsel. The damselfish calls are intermixed with the crunch and scrape of parrotfish biting algae off hard coral skeletons (**Audio file** at bit.ly/Freeman-Scrape1), the lower frequency purrs of groupers, the chatter of reef fish searching for food (**Figure 3**), and the ever-persistent snaps, clicks, and pops of hundreds of thousands of invertebrates within and atop the coral reef structure that forms the base of this ecosystem.

Soundscapes provide a fascinating way of monitoring and understanding ecosystems in single snapshots of time, but the story does not end there. The soundscape, or acoustic signature, of a healthy reef is so ingrained in the corals and fishes that make up the reef community that their larvae may use sound to help find an optimal place to settle out of their pelagic phase before "selecting" their final home (e.g., Gordon et al., 2018). Examples of sounds of a dying reef are available at bit.ly/dyingreef and of a healthy reef at bit.ly/Reefsound. These videos have striking visuals, but if you close your eyes, you could just as easily imagine being in a tropical rainforest, the terrestrial sister ecosystem to the ocean's coral reefs, two of the centers of biodiversity on planet Earth.

Healthy reef sounds attract greater numbers of certain types of reef fish larvae and coral larvae, as demonstrated

Figure 3. *A healthy coral reef. The reef scene from Indonesia with healthy coral and abundant fish shows the potential biodiversity and biomass in a coral reef ecosystem. Coral reefs are sometimes deemed the rainforests of the sea because they have so many species occupying the ecosystem. Such a rich ecosystem has an equally rich soundscape when in good health. Photo by L. Freeman.*

in a series of experiments and in situ observations (e.g., Boulais et al., 2024). Larvae spend several weeks in a planktonic phase adrift in the ocean. Once the planktonic larval stage is complete, the animals undergo further metamorphosis into a juvenile that resembles the adult. At that time, there are several environmental cues that the larvae use to determine an optimal place to end their planktonic phase by sinking to the ocean floor, hopefully on a coral reef, and take up residence for their adult lives.

One of those cues for coral reef fish and corals themselves is healthy reef sounds. However, although a number of scientists have shown that healthy reef sounds enhance larval recruitment, it is not yet clear exactly which component of healthy reef sounds is creating a cue for the larvae. Understanding how and where healthy reef sounds can be used to enhance restoration, coral farming, and conservation efforts is an exciting intersection of underwater soundscapes, coral reef ecology, and marine conservation. Furthermore, coral reef soundscapes are now well enough understood to not only track the current health status of a particular ecosystem but to also actually use the essential ocean variables of ocean sound as a means of identifying and tracking ecosystem recovery on restoration projects (Lamont et al., 2022).

Seagrass beds and marine algae also contribute to the soundscape (Freeman et al., 2018), though not in the same way that fishes vocalize or shrimps snap. Seagrass and algae emit sounds as a by-product of photosynthesis when the oxygen waste product is exuded from the plant along the surface and forms bubbles. As the bubbles grow, buoyancy forces exceed the surface tension (also known as the van der Waals force), physics forces drive the bubbles upward away from the plant, and the bubbles produce sound as they rise through the water column at a frequency proportional to their size. This ringing is at higher frequencies than typical reef sounds but is still audible to human hearing if played back from a hydrophone recording. The bubbles produce a series of short-duration transient sounds that are typically present in such large numbers that they give the impression of a lasting high-frequency ring.

Anthropogenic Climate Change

Underwater acousticians are continuing to discover just how critical soundscapes are to marine life, with a growing group of scientists contributing to the field. The nascent observation that healthy reef sounds improve larval recruitment is still being tested in new environments and with additional species. As we work to understand the intricate relationships between ocean ecosystems and acoustics, we are simultaneously documenting the changes in those ecosystems being driven by climate change. Understanding and mitigating these changes, which are caused by industrial enrichment of greenhouse gases in the Earth's atmosphere, is one of the grand challenges of our time. Humans have perturbed the Earth system such that the ocean environment itself is changing on a regional scale.

The impacts of anthropogenic climate change exacerbate a myriad of issues even well beyond the need of animals to use the sounds; these issues include things such as food security and national security. Humans have emitted 2.3 trillion tons of CO_2 since the Industrial Revolution on a timescale of hundreds of years, far more rapid than past geological climate oscillations. The plants and animals that comprise ocean ecosystems have honed their behaviors over millions of years of evolution, including their use of sound production and of their soundscape. Scientists are just beginning to understand the intricacies of some ocean soundscapes and how critical they are to the animals that reside in oceans, bays, and estuaries; at the same time, the ocean itself and likely the associated soundscapes are changing rapidly. Although nations are committing to reducing emissions now, significant effects have already changed the Earth climate system to include ocean warming, ocean acidification, reduced sea ice, increased storm frequency and severity, atmospheric rivers, and modified precipitation patterns (see the Intergovernmental Panel on Climate Change Sixth Assessment Synthesis Report at ipcc.ch/ar6-syr). Many of these weather and physical impacts are directly translated as underwater ambient sound sources, be it rainfall, wind, or changing sea ice dynamics.

Understanding how climate change is shifting ocean environments is paramount to providing effective tools for marine conservation and to developing and maintaining a scientific record of how the ocean and its inhabitants interact without the influence of human activities. Many of the physical and chemical shifts affecting the global oceans are not only well underway but are accelerating. For example, ocean surface warming from 2010 to 2019 has accelerated to 4.5 times the average per decade (Garcia-Soto et al., 2021). The ocean's decadal warming rate or temperature increase over 10 years from 2010 to 2019 is twice that of the previous decadal time period (2000–2009), and the circulation rates of the Atlantic Ocean are slowing down as well (Garcia-Soto et al., 2021).

Changing Seawater Properties and Acoustic Propagation

Understanding soundscapes is not only limited to tracking acoustic sources but also to the ability of signals to reach a particular receiver or the ability of sound to travel through seawater. Climate change will shift the acoustic properties of seawater, and thus the velocity of sound through a particular area of the ocean. Although temperature is a key driver of sound speed in water such that higher temperatures result in an increased sound speed, pH will have profound impacts, particularly at high latitudes, such that lower pH values are associated with higher sound speed. Ocean pH is regulated by the global carbon cycle and uptake of CO_2 in the ocean. The ocean and atmosphere seek equilibrium and as atmospheric CO_2 increases in the atmosphere, the ocean also absorbs additional CO_2. This additional CO_2 dissolved in seawater leads to a series of chemical reactions between the gas and seawater, which affects pH or ocean acidity in making the water more acidic. This is more pronounced at higher latitudes because colder water, such as Arctic and Antarctic regions, can absorb more CO_2. For example, in the Arctic, pH is expected to drop from approximately 8.1 to 7.9 in the next 30 years, resulting in an increase in sound propagation for frequencies up to 10 kHz, with the effect most pronounced at 900 Hz (Duda et al., 2021). The chemical and physical laws driving these interactions also apply to lakes and rivers, which are similarly undergoing significant environmental shifts with rapid increases in atmospheric CO_2.

Modeling sound speeds from temperature and salinity data in future climate scenarios reveals global changes with particularly dramatic shifts in high-latitude environments (**Figure 4**) (Affatati et al., 2022). It is important to note that this result does not consider the effects of ocean acidification on sound propagation (described by Duda et al., 2021). However, this fundamental shift in the ability to send and receive information acoustically will potentially have impacts on several marine mammal species that rely on sonic and ultrasonic acoustic communication for social dynamics, mating, navigation, and feeding. Such effects would be most likely at high latitudes, where animals may need to adjust their acoustic communication frequency, duration, or call style to account for changes in sound speed and different water layers that trap or reflect sound (ducting). The change in sound speed and sound propagation would likely be secondary effects to changes in ocean temperature limiting suitable ranges for marine mammal species and reduced ocean pH threatening a major prey source of krill that would not be able to form their exoskeletons and survive in the more acidic waters. Marine species will need to adjust their ranges to find niches of water space that have the temperature, pH, and prey that they require to survive. Data from the National Oceanographic and Atmospheric Administration and other long-term acoustic monitoring programs are tracking marine mammal species distributions and biogeographic ranges because range shift is expected in the coming decades of ocean warming. As soniferous animals relocate their habitat range, they are introducing sound sources to the soundscape of their new home and removing their acoustic signals from the waters that they have left behind.

Acoustic Thermometry of the Ocean

Perhaps the best-known example of the interplay between climate change and underwater acoustics is acoustic thermometry of the ocean (ATOC) as initially proposed by Munk (1993). In short, warmer water has a higher sound speed. If you consider a source and receiver from the same respective locations in times when the ocean between them is warmer, the travel time should be reduced accordingly. This method averages ocean temperatures across depths, or ocean heat content, over large scales, and, in theory, repeating long-range propagation experiments with the same sources and receivers at the same locations would allow for measuring ocean warming across scales of thousands of kilometers, if sufficient samples were collected. ATOC has also been the basis for modeling studies that reveal the shift in sound propagation across large scales under different climate warming scenarios from global climate models (Dzieciuch, 1994).

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On *Across Acoustics*, editors of the *JASA* special issue on this topic explain how climate change has led to a reduction in amount of ice covering the Arctic as well as the structure of the ocean—impacting everything from communication of marine life to human navigation systems.

Read more articles on environmental soundscapes at **bit.ly/3vGswzJ**

Climate Change Impacts on Underwater Acoustic Sources

Acoustic sources, or signals contributing to ocean soundscapes in different regions, will be shifted in several ways because of climate change. Passive acoustic monitoring networks contribute to our understanding of precipitation patterns and storms, particularly in more remote sections of the ocean where weather stations may not be available or as densely spaced (Pensieri and Bozzano, 2017).

The same marine life that acousticians and marine biologists are describing as major contributors to underwater ambient noise is under a dual threat from greenhouse gases shifting the physical and chemical parameters of their habitat as well as humans actively removing animals from the system for food. Some of these animals, such as corals and marine mammals, have been identified as endangered species, whereas others are identified as at risk from climate change impacts, in both cases meriting targeted conservation and restoration efforts. Acoustics has a key role to play in that effort, both in terms of monitoring marine life and as a means of enhancing results.

Conservation efforts in the past decade or so have been incorporating soundscapes to encourage larval recruitment and retention at restored coral reef sites (Lamont et al., 2022). Passive acoustic monitoring is becoming a more frequent tool in tracking marine conservation efforts and marine mammal species ranges and numbers. Passive acoustics is also used by fisheries ecologists to track individual fish calls and group spawning events (Souza et al., 2023) and even to track invasive versus native species in key environments (Amorim et al., 2023). Fish calls are reliably utilized to identify certain fish to the species level, and the underwater acoustics community has begun to gather representative recordings of fish vocalizations into an open access library of fish sounds to improve consistency across scientific studies (Looby et al., 2023).

Of particular interest, an observational study has shown that marine ecosystems respond to warmer seawater by increasing their acoustic output (Freeman et al., 2023). Snapping shrimp, a key contributor to ocean sounds, particularly in shallow near-shore areas, have been observed to increase their snap rate in warmer waters, with the snap rate doubling in association with 5°C of warming. This was initially observed from long-term passive acoustic monitoring data and then tested rigorously in laboratory experiments (Lillis and Mooney, 2022).

In another case of observed changes in ocean sounds linked to ocean temperature, a collection of long-term coral reef (**Figure 4**) soundscape records in both Hawai'i and Bermuda showed an overall increase in ambient noise in frequency bands associated with fish calls, parrotfish scrapes as they fed on coral polyps, and invertebrate activity with increasing temperature (Freeman et al., 2023). In the case of calls or vocalizations, the nonvocalization behaviors of invertebrate activity and feeding are incidental acoustic signals rather than intentionally produced sounds. Each of these type of acoustic signals was considered separately and filtered by their predominant frequency band, with fish calls being the lowest at 500-1,000 Hz followed by parrotfish scrapes at 1-2 kHz. Sound level as pressure spectral density in each frequency band was calculated over several years of data and compared with ocean surface temperature to identify this trend. Each individual metric showed the same positive correlation with ocean surface temperature.

Moreover, despite being situated in different ocean basins and latitudes, there was a remarkable overlap in midfrequency ambient noise (2-10 kHz) associated with invertebrate activity on coral reefs and seawater

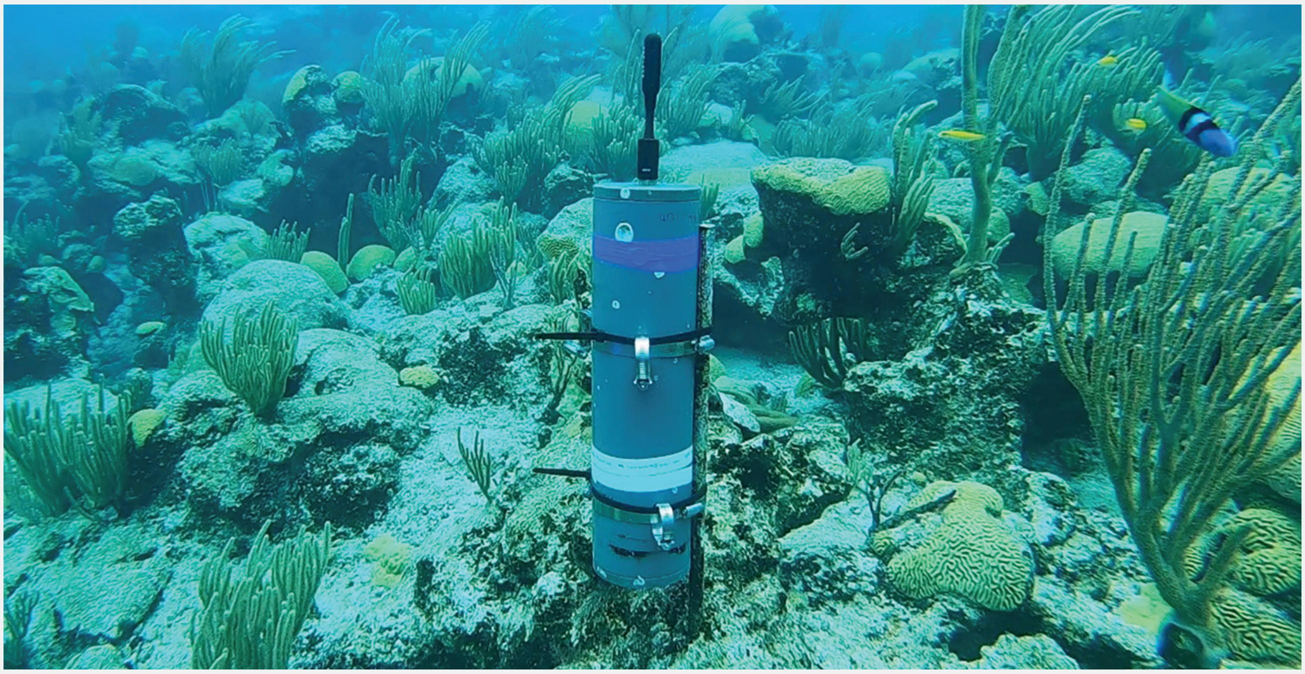

Figure 4. *Passive acoustic monitoring of temperate coral reefs in Bermuda. Self-contained hydrophone recording packages include the hydrophone (small black antennae on top of the instrument) attached to a waterproof housing that holds a receiver, data storage, and batteries. These systems are installed on the seafloor for months or years at a time and exchanged by divers to maintain the time series. Photo by L. Freeman.*

temperature. The species composition of coral reefs in Bermuda and Hawai'i are unique to each other, suggesting that the observed trend is not the response of one or two primary noisemakers but rather a broader trend in activity levels and sound production by invertebrates in reef environments as a function of water temperature. Other contributions to the soundscape such as physical noise from wind, rain, and storms were tested as well but did not show significant linkage to ocean temperature (Freeman et al., 2023).

The Arctic is being disproportionately affected by ocean and atmospheric warming due in large part to the positive feedback cycle of ice albedo, which is the ability to reflect solar radiation. As sea ice and land ice melt, they reduce in thickness and their albedo is also decreased. This leads to more heat transfer and faster melting. In this particularly dynamic environment, there is a confluence of shifting noise sources contributing to the soundscape and rapidly changing physical and chemical ocean parameters affecting sound propagation through water. A 2022 special issue of *The Journal of the Acoustical Society of America* on Ocean Acoustics in the Changing Arctic (see bit.ly/3ITvT9y) (Worcester et al., 2022) noted that acoustic systems have a special role to play in making measurements of the ice-covered Arctic Ocean.

Conclusions

Nearly all underwater environments are being affected by climate change and human activity, and effects on some regions are more pronounced than on others, such as we are seeing in the Arctic. In all cases, soundscape studies will help us better understand what is happening across space and time by taking advantage of the unique properties of sound propagation through seawater. Soundscapes are being used in coral reef restoration efforts both as a means of tracking ecosystem health and as a means of attracting fish and coral larvae to restored sites. Because the ocean is considered for a larger number of marine CO_2 removal efforts, soundscapes offer the ability to track impacts on native marine species as well as to monitor seawater temperature, pH, and chemical makeup as it affects acoustic propagation. There is a key interplay between understanding marine soundscapes and using that knowledge to support ocean stewardship, conservation, and climate mitigation efforts.

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The Past Has Ears at Notre-Dame Cathedral: An Interdisciplinary Project in Digital Archaeoacoustics

Sarabeth S. Mullins and Brian F. G. Katz

The concept of a cathedral frequently suggests a static object where, once the final stones have been placed, the structure remains impervious to time. It is tempting to think of the great cathedrals as stoic white monuments filled with stone and, perhaps, the light of stained glass. However, the great cultural legacy of the medieval cathedrals is a legacy of change. Cathedrals continue to change long after the completion of their initial structure as their occupants discover new needs, new fashions, and new priorities. Combined with acts of humans, nature, and the passage of time, cathedrals are subject to constant evolution. The Cathédrale Notre-Dame de Paris is an excellent example of this.

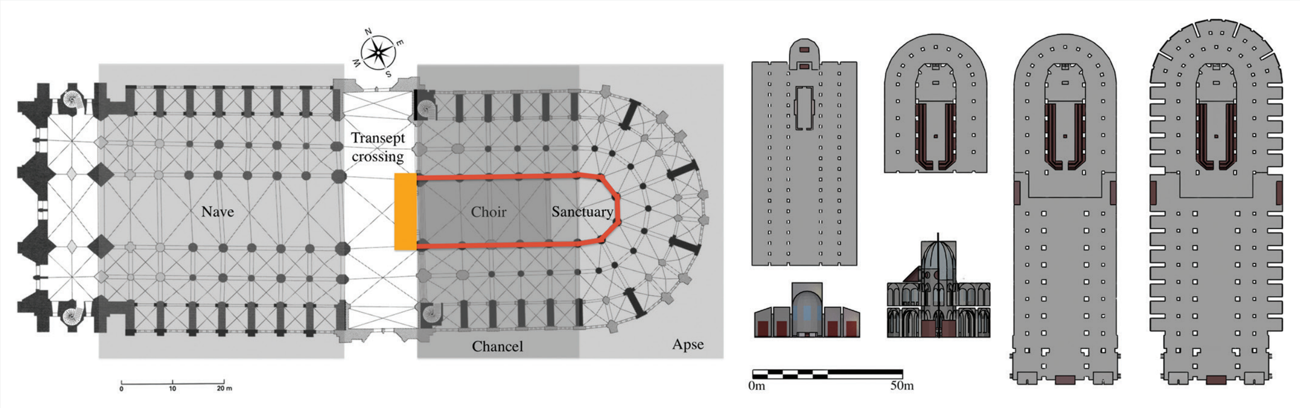
The recent fire at the cathedral (see youtu.be/jjPeEIgf0dw) has motivated a series of studies attempting to better understand the acoustics of Notre-Dame, its evolution over the centuries, and its influence on music, extending to predictions in the aid of its restoration. We present here an overview of the interdisciplinary work around the research into the acoustic history of the Cathédrale Notre-Dame de Paris. A light-hearted introduction to cathedral acoustics and our work can be watched in the popular science video (see youtu.be/aJvvkl3qrXM) made in collaboration with our team. But first, we present an overview of the cathedral and its long history.

Living Building

Anatomy of a Cathedral

In the following discussion, we use some technical terms to discuss locations within the cathedral. As seen in **Figure 1,** Notre-Dame de Paris is an approximately rectilinear building with an internal structure resembling a cross. The focus of ritual use is the *apse*, a semicircular termination of the cathedral in the east. The *nave* is an elongated area in the western portion of the Cathedral and is separated

Figure 1. ***Left***: *floor plan of Notre-Dame with architectural terms, with the clôture (**red**) and jubé (**orange**).* ***Right:*** *acoustic model floor plans and elevations of cathedrals built on the Île-de-la-Cité.* ***Left to right:*** *the pre-Gothic basilica underneath Notre-Dame's parvis (before 1163); Notre-Dame at its consecration (1182); the termination of the nave (~1220); and the termination of the lateral chapels (~1350).* ***Right*** *reproduced from Mullins et al. (2022), with permission.*



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from the apse by a transversal aisle called the *transept*. The apse contains the *liturgical choir*, a consecrated area containing both the choir stalls for high-ranking church dignitaries and, historically, the grand altar and important relics within an area called the *sanctuary*. For most of Notre-Dame's history, the liturgical choir was separated from the rest of the apse by a tall stone wall called a *clôture (***Figure 1**, *red)* and access was limited by a large gate (*jubé*; **Figure 1**, *orange*) standing between the transept and the western end of the choir stalls. When considered vertically, the cathedral begins at the ground floor. The *triforium* level is located one floor above the ground (seen in the section drawing of Notre-Dame in **Figure 1**), and the stained glass windows are found in the *clerestory* level just below the vaulted ceiling. An online 360° image virtual tour is available that can help to better understand the space (see t.ly/J8on6).

Construction

Beginning its construction in the 1160s, Notre-Dame de Paris was not the first ecclesiastical building erected in Paris on the Île-de-la-Cité (see t.ly/9n0Do) nor was it the initial tribute to the Virgin Mary on the island. Rather, scholarly evidence suggests that the impetus behind Notre-Dame's construction lay in the endeavor to restore and rebuild the infrastructure of the *chapter* (a collective of priests, canons, and clerics affiliated with a specific church or cathedral) following the Viking Age. Notre-Dame emerged as one of the earliest manifestations in France of Gothic architecture (Hourihane, 2012). Spearheaded by Bishop Maurice de Sully (see t.ly/MyPHC), developmental efforts commenced on the apse in the spring of 1163 (Berger and Sandron, 2019) while existing church structures underwent demolition to clear the grounds for the burgeoning cathedral. These structures included a small chapel dedicated to Mary beneath the contemporary transept and a large basilica situated beneath the present-day *parvis* (churchyard, in front of the western entrance) of Notre-Dame (Viollet-le Duc, 1854/1868, §*Cathédrale*; Barbier et al., 2019). The inaugural phase of construction, culminating in the full completion of the apse, concluded in 1182 with the consecration of the grand altar (Sandron, 2021).

With this phase of construction, a significant retaining wall was erected to separate the consecrated choir from the on-going construction, allowing religious ceremonies to proceed without disruption. By the 1220s, the nave had been completed, and a new campaign began to expand the cathedral's perimeter with 35 chapels between the flying buttresses (see **Figure 1**). By the 1330s, work on the lateral chapels was completed, and the external structure remained largely unchanged until Viollet-le-Duc's nineteenth-century renovations. His excavations unveiled early design modifications, including circular attic openings below the stained glass windows near the ceiling. Originally smaller, the windows were enlarged after a fire in 1218 in an attempt to prevent future incidents.

Decoration

The chapter's presence within the cathedral quickly led to the decoration of the interior, including the choir stalls. A large stone jubé was constructed between the transept and the western choir entrance in 1135, and by 1350, the remaining sides were surrounded by highly ornamental stone walls (a clôture) (Gillerman, 1977), creating a ceremonial enclosure in the heart of the Cathedral. Church records contain inventories of tapestries, carpets, curtains, and hangings that decorated the interior of the consecrated space (Wright, 1989a). Over time, nobles and high clergymen were buried in the apse and choir and funerary monuments dotted the church. Statues, funded by Parisians, adorned the space, including one of King Philippe Le Bel placed in the transept after a victory in 1304. The highlight was a towering statue nearly 9 m tall of St. Christopher erected in 1413 in the nave (see t.ly/mFIY5) (Sandron and Tallon, 2020). Patrons enthusiastically adorned the lateral chapels. Over time, evolving tastes and trends influenced the style and character of these decorations, mirroring contemporary culture.

Living Heritage

The cultural heritage of Notre-Dame de Paris can be traced back to its initial occupancy, circa 1182. Next, we introduce a selection of the traditions housed within the cathedral for those with an interest in sound. **Figure 2** presents a companion timeline to this discussion, highlighting various historical, architectural, and musical events in the history of the cathedral.

The School of Notre-Dame and the Development of Written Polyphony

Notre-Dame de Paris boasts a rich musical legacy dating back to its inception. Spanning over 850 years, the cathedral has witnessed the evolution of music, with its most notable contribution being the establishment of the

Figure 2. *Time line of relevant historical and construction events (**top**) and musical periods (**bottom**) of Notre-Dame for general reference. Rest, Restoration.*

Notre-Dame School of Music (see bit.ly/4bWjJdh). This group of composers and musicians introduced a virtuosic style of singing, enhancing single-melody plainchant (a type of liturgical song in which religious texts are sung on a single melodic line and in unison) with intricate ornamentation provided by multiple soloists. While polyphonic music (i.e., music with more than one melody) existed in Western Europe prior to the School of Notre-Dame, it was largely improvisational and confined to specific regions or time periods (Everist, 2011).

The Notre-Dame School is particularly associated with the musician Léonin (active 1160–1200; see t.ly/2JQRg) and his successor Pérotin (active 1180–1220; see t.ly/PCi3m), who expanded the music of Léonin into four-voice polyphonic arrangements. The historical record indicates that church authorities mandated the development of special musical arrangements to mark important dates in the church calendar (Everist, 2011). Thus, while a simple plainchant was performed daily for the mass and the intermittent prayer services of the church, the performance of Parisian polyphony was associated with the high feast days of the church calendar when the choir of Notre-Dame was richly decorated with velvets, tapestries, and other acoustically significant textiles (Wright, 1989b). Although Notre-Dame is not the only location to have a known relationship between composer and architecture, the fast pace of construction on the site in parallel with the rapid development of musical styles is suggestive. One wonders if the relationship between cathedral and musician influenced the development of the Notre-Dame School given the temporal correlation between cathedral occupancy and the active years of Léonin and Pérotin. Until recently, musicologists and historians could merely speculate about such a relationship, as later construction at the cathedral has entirely altered the acoustic characteristics of the twelfth and thirteenth centuries.

Medieval Organ

During the latter part of the fourteenth century, permanently installed pipe organs began to be installed in sizable churches and cathedrals, marking a significant evolution in their role within liturgical, devotional, and communal contexts (Ros, 2019). Notably, Notre-Dame housed at least two Gothic organs during this period: one dating back to the fourteenth century (referred to as Organ I) and another from the fifteenth century (referred to as Organ II). The earliest documented mentions of an organ within the records of Notre-Dame's chapter date even earlier, to 1332 where payment to an organist is noted, and to 1333-1334 when a bell was placed in the choir to complement the organ (Hardouin, 1973). These references likely allude to an earlier, more portable iteration of the instruments we call Organ I and Organ II.

In the fourteenth century, the organ's role was primarily reserved for 23 major feasts and special events. Although our understanding of the repertoire, both written and improvised, is limited today, glimpses of its nature are gleaned from subsequent written accounts. The transept in the Cathedral serves as a significant acoustic divider, creating two distinct zones due to its spaciousness and lack of partitioning walls. This acoustic division reflects the priorities of the original builders but no longer aligns with modern expectations of the Cathedral. Functionally, the instrument served two primary purposes, closely intertwined with the liturgical proceedings within the choir and the activities unfolding in the nave. First, it engaged in dialogue with and potentially provided accompaniment to the choir ensconced within the apse. Second, it played pivotal roles in inaugurating and concluding the liturgy, supporting processions, and dignifying the arrivals of esteemed figures such as kings or visiting dignitaries (Wright, 1989b).

Revolution and Restoration

The French Revolution of 1789 significantly impacted Notre-Dame Cathedral, leading to damage and neglect as it became a target of revolutionary fervor. It was briefly transformed into a secular space during this time. However, post-Revolutionary efforts, including initiatives in the nineteenth century led by architect Eugène Viollet-le-Duc, helped restore the Cathedral's Gothic features. Despite the damage inflicted, the Revolution spurred endeavors to preserve and restore Notre-Dame, emphasizing its enduring significance as a symbol of French heritage.

The 2019 Fire and Acoustic Cultural Heritage

On April 15, 2019, a fire broke out in the attic of the Cathédrale Notre-Dame de Paris (for images, see t.ly/hXjDt). The damage caused by the incident destroyed the roof and created three significant holes in the vaulted ceiling as the spire and debris collapsed. Concerns arose about the building's structural stability, along with inquiries regarding the loss of Notre-Dame's historic acoustics. Despite erroneous reports from some international journalists suggesting the loss of these acoustics, documentation on Notre-Dame's acoustics had actually commenced several years before the incident.

Recent UNESCO (2017) resolutions and conventions underscore the importance of preserving, studying, and recreating the soundscapes and acoustics of historical sites. Advancements in computing power now facilitate detailed acoustic simulations for complex structures like theaters, concert halls, and cathedrals.

Living Acoustics

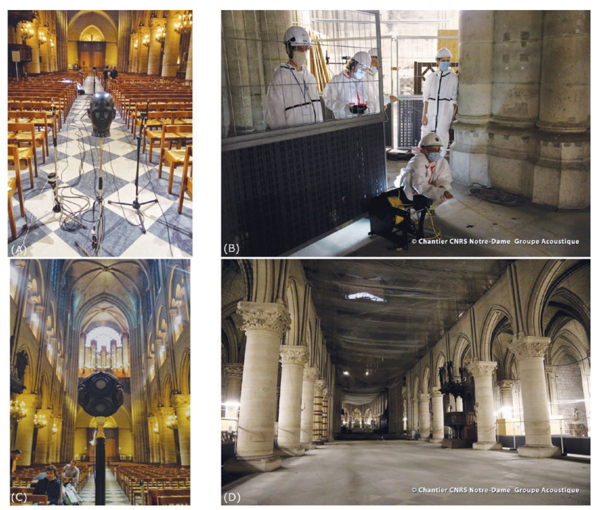
Acoustic Measurements

Despite the notoriety of the cathedral, there are few examples of published data on the acoustical parameters of this space. A few early twenty-first-century studies reported varying reverberation times for the modern cathedral (6.5-7.5 s at 500 Hz), where concert halls have a typical upper bound of 2.0 s. Our laboratory conducted two measurement campaigns prior to the 2019 fire, with additional measurements taken afterward to assess changes in the building's acoustics. The first campaign in 1987 utilized an impulsive source (balloon popping) retrieved from an acoustic study related to a potential organ installation. Although limited by incomplete stimuli details, such as anechoic signals and sweep stimuli parameters and despite not being omnidirectional sources, balloon pops provided valuable impulsive signals for certain applications (Pätynen et al., 2011).

Later, as part of a French research project on binaural listening (FUI BiLi), we made a series of acoustic measurements in 2015, almost four years to the day before the 2019 fire (Postma and Katz, 2016). These detailed measurements were made with the modern sine-sweep technique, with multiple receiver positions spread over a large portion of the floor area, including binaural and Ambisonic microphones at select positions.

As part of our role as coordinator of the Acoustics Working Group of Chantier Scientifique, the group organized by the French national science center and the Minister of

Figure 3. *Prefire measurement photos.* ***A:*** *setup for binaural room impulse response measurement and the miniature dodecahedron source. Postfire measurement photos.* ***B:*** *measurement team in protective gear in the safe zone;* ***C:*** *driving the remote vehicle that towed the microphone arrays; and* ***D:*** *view of the nave, off-limits to all persons, after the initial debris cleanup.* ***C*** *and* ***D*** *reproduced from acoustic-task-force-notre-dame.dalembert.upmc.fr, courtesy of Chantier CNRS Notre-Dame Groupe Acoustique.*



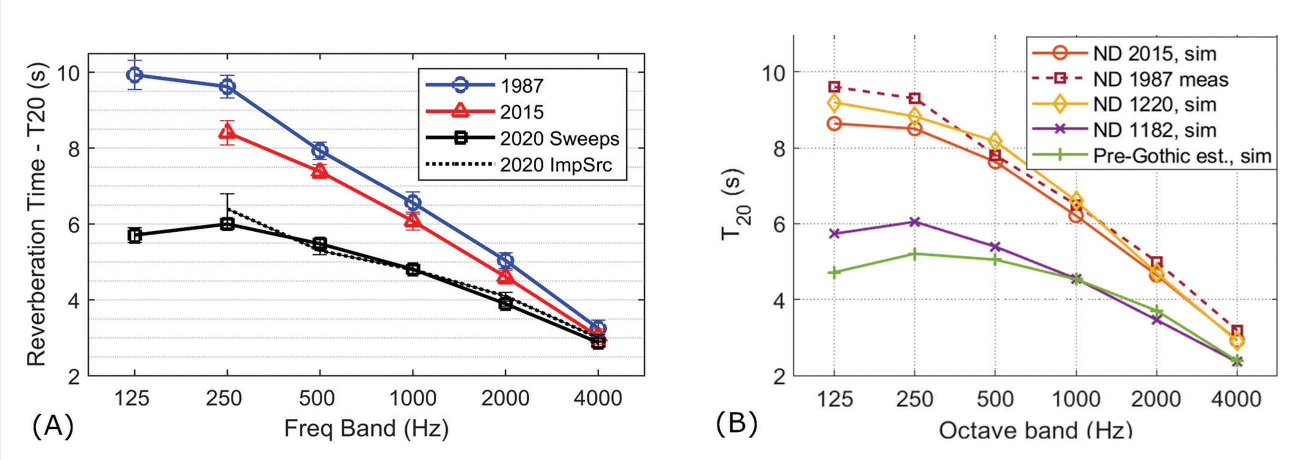


Figure 4. *Mean reverberation times (*T20*) over omnidirectional receivers for measured (meas;* **A***) and simulated (sim;* **B***) conditions for Notre-Dame (ND) and the speculative pre-Gothic church. Freq, frequency; ImpSrc, sweep and Impulsive type source stimuli.*

Culture to provide scientific support to the restoration team (Dillmann et al., 2024), we were granted access to the site for a third measurement campaign in June 2020 (Katz and Weber, 2020). The falling spire damaged the central part of the transept/altar marble floor, leading to restricted access to the central nave and transept due to the risk of falling debris and structural instability. The choir was also inaccessible due to debris. Side altars were used for storage, and scaffolding was installed for organ removal, along with a protection barrier enclosing the central nave. See the photos in **Figure 3** and a video documenting the measurement session (see youtu.be/YLi7ASosKvw, with English subtitles).

One can see the general decrease in reverberation times (**Figure 4A**) (Katz and Weber, 2020). We eagerly await assessing the Cathedral's acoustics in its updated state once the reconstruction is complete and the interior scaffolding is removed.

Historic Modeling/Acoustics

As a part of the 2015 measurement campaigns, a calibrated acoustic model of the twenty-first-century Cathedral was made (Postma and Katz, 2015). This was used as part of a research project on the use of binaural audio for media productions, where the aim was to create a virtual 360° re-creation of a concert in Notre-Dame where one travels around the Cathedral on a magic carpet (see bit.ly/3OZxf65; youtu.be/qcOPuIVpXxk), allowing for an appreciation of changes in acoustics with one's position in such a monumental space. Following the 2019 fire, it became evident that our model had broader applications. Through the Chantier Scientifique initiative, we have delved into detailed studies of the Cathedral's historical configurations and their cultural significance. Collaborating with experts in art history, architecture, and musicology, we have utilized the model to explore the acoustic impact of various elements such as draperies, organ placements and the enduring influence of paintings during Notre-Dame's early periods. Furthermore, we investigated the auditory experiences of significant events over the centuries, like the Festival of Reason, Napoleon's coronation, and the implications of Viollet-le-Duc's restoration efforts on the Cathedral.

A speculative model of the pre-Notre-Dame church was made following the archaeological traces found underneath the parvis, outlining a rectilinear building ≈35 m wide and ≈70 m long (Barbier et al., 2019), with two sets of side aisles flanking the main aisle. There is no record of the height of the ancient structure. To aid in the development of the speculative model of this building, a well-preserved, contemporaneous basilica-style church was identified and selected to stand in as a possible representation of the building. The church selected, the *Basilica of Santa Sabina all'Aventino* (see basilicasantasabina.it), is located on Aventine Hill in Rome, Italy. Originally built in the fifth century, the interior of the basilica has survived largely unmodified to the modern era, maintaining the characteristic semicircular apse and flat, wood-paneled ceiling common to basilicas of the early Middle Ages. The acoustics of Santa Sabina were measured and reported in Cirillo and Martellotta (2005), and the base model was created and calibrated to the measurements following established procedures (Postma and Katz, 2015).

Because materials from the demolished preexisting church were reused for the construction of Notre-Dame, the same acoustical material properties were used to ensure continuity between the models. After verifying the Santa Sabina model calibration with measurements, the model was morphed to match the dimensions of the pre-Gothic church, maintaining the calibrated material properties as well as key design elements from Santa Sabina. Without knowing the height of the historic basilica, surviving contemporaneous basilicas of similar or larger size were consulted to maintain a consistent proportion of width and height for the center and side aisles, including *San Paolo fuori le Mura* (Rome), *Sant'Apollinare in Classe* (Ravenna, Italy), and the *Church of the Nativity* (Bethlehem, Israel).

The models of the Cathedral, representing the 1182, 1220, and 1225 states, were based on the 2015 calibrated model of Notre-Dame. The interior geometry of the calibrated model was altered to reflect the commonly held view of the construction timeline, with attention paid to changes in furnishings and decorations. Additional models were selected to examine the closing and completion of the nave, spanning approximately 1225 to 1320. These states include the "finished" state of the building when the nave was completed in 1220, several intermediate states as the chapels were built, and the state in 1320 after all the side chapels were completed. The results of some of these models in comparison with the acoustic states from the twentieth and twenty-first centuries can be seen in **Figure 4B**.

To accurately re-create the historical states of the church, it was important to verify the acoustic properties of textile and decorative materials present. Various historical materials were measured to assess their absorptive qualities. These included carpets from the liturgical choir, tapestries from workshops supplying the cathedral, and velvet hangings used for special occasions. Additionally, absorption coefficients were measured for loose straw and woven jute because it was common practice in the Middle Ages to use these materials for flooring in high-traffic areas.

These measurements enabled us to establish the appropriate material properties for inclusion in the acoustic models, although some uncertainties persist. For example, the impact of medieval clothing on audience absorption remains unknown because modern audience absorption coefficients are based on contemporary clothing. Similarly, the application of layers of whitewash to Notre-Dame's stone walls during its seventeenth-century renovation raises questions about the long-term effects on the characteristics of the Lutecian limestone. Despite these uncertainties, efforts have been made to acoustically represent the decoration and materials of the time in the historical models.

The Organs

We used the models to investigate the origins of the first medieval organs. The location of the fourteenth-century organ is uncertain, but it's believed to have been built in the second half of that century during renovations. Organ I is poorly documented, with limited information found in the Cathedral's chapter registers from 1426. These records mention that the organ blocked a window on an exterior wall. Six assistants operated the bellows using a wheeled blowing engine, and it was referred to as a "large organ" by a visitor in 1414 (Wright, 1989b).

We examined the acoustic effects of the organ's position and mounting height. Evidence from various sources suggests that the organ likely protruded from the triforium level, referred to as a "swallow's nest" (see bit.ly/3ST6PUw), somewhere in the nave of the Cathedral. Although the exact position within the nave remains uncertain, the southern wall is considered the most probable due to better climatic conditions because the wall does not receive direct sunlight. Comparing locations between the two nave positions reveals that although sound pressure levels are relatively high and uniform throughout the nave, an organ positioned in the second bay (closest to the nave) would be more beneficial to the choir due to its proximity to the apse. Additionally, positioning Organ I in the second bay above the chapel dedicated to St. Augustine aligns with the theological significance of music in his teachings (Canfield-Dafilou et al., 2023). **Figure 5** shows the results of the room acoustic parameter *center time* (i.e., the center of gravity of energy in the room impulse response) analysis of the various locations considered. We opted for the use of center time as a more general notion of musical clarity compared with other parameters because it provides for a better interpretation of the energy distribution and is not limited in musical style in its interpretation (e.g., liturgical music found within Notre-Dame).

Acoustics of Gothic Columns

In large ancient structures like Notre-Dame, various columns and piers with distinct shapes scatter sound waves in all directions, termed volumetric diffusers. Unlike modern acoustic surface diffusers that diffuse sound at wall reflections, cylindrical obstacles like those found in buildings like Notre-Dame disperse waves in all directions. Examples include reflector canopies above concert hall stages and hanging panels in reverberation chambers. Although these objects typically have less impact on longer wavelengths, considerations for their curvature at lower frequencies are necessary. The rows of columns surrounding the nave in Notre-Dame act as lateral reflectors, reflecting Gothic architectural styles over centuries. Although columns produce limited reflections due to their finite size, these reflections arrive considerably earlier than most wall reflections.

We also investigated the sound scattering of various designs using physical scale models and numerical simulations. Both methods demonstrated strong agreement, validating the results. The scattered field showed audible reflections in all directions, with temporal spreading influenced by the shape of the scatter (Weber and Katz, 2022). Piers with smaller features can produce diffuse reflections similar to surface diffusers. Spectral differences between piers suggest the possibility of distinguishing between their reflections, indicating the need for further perceptual evaluations in realistic settings.

Figure 5. *Center time (T_S) for unoccupied condition, comparing organ position/orientations (**black arrows**). **Left to right:** location of the contemporary grand organ in the tribune; two positions in the nave; and the location of the contemporary choir organ. Lower values indicate earlier arriving energy and hence more musical clarity. Reproduced from Canfield-Dafilou et al. (2023), with permission.*

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Living Culture

The historical and culturally significant practices at Notre-Dame can be categorized into two groups. The first comprises singular events such as the Cathedral's conversion to the Worship of Reason during the French Revolution. This provides context but is not acoustically focused. The second includes long-term developments like the Notre-Dame School, preaching practices, and funerary traditions. Of particular interest is the Notre-Dame School, which emerged alongside the Cathedral's construction and had international influence. The historical state acoustic models were used to explore the relationship between architecture and music during this period. Two hypotheses were formed. The development of the Notre-Dame School was influenced by the Cathedral's acoustics and the new style was well-received by clergy members. We carried out two experiments designed to test these hypotheses based on research into musical performance and room acoustics.

Experiments

In the first experiment, a real-time auralization system was set up in an anechoic chamber to simulate different acoustic environments. The system rendered convolutions of binaural room impulse responses derived from acoustic models, modified to remove direct sound and floor reflections. Medieval music specialists were asked to sing three musical excerpts from different periods within the Notre-Dame School's timeline. These performances were recorded in various virtual acoustics, including those of the pre-Gothic cathedral, Notre-Dame from 1182, 1225, and 1320, as well as in an anechoic condition. Each choir performed the three songs three times each, repeating the procedure in the five acoustic conditions, resulting in 180 audio and video recordings per session. This setup allowed for testing the impact of changing acoustics on musical styles. If the hypothesis holds true, cleaner and more synchronized performances would be expected in the 1182 acoustics during the Notre-Dame School's pieces. Alternatively, if the null hypothesis is confirmed, no significant interaction between acoustic and performance parameters or even a negative impact on synchrony and performance metrics would be observed.

The ongoing analysis of audio and video data has revealed several intriguing trends. Similar to observations in solo vocalists (Luizard et al., 2020), the two choirs exhibit different adaptive behaviors. For instance, one ensemble's performance speed varies significantly across tested acoustics, whereas the other ensemble shows no statistically significant change.

The second experiment aims to understand how the high clergy may have perceived new musical styles in the cathedral. Singing experiments were recreated for offline listeners to assess three music genres across the acoustic conditions from the first experiment, listening from the perspective of the bishop. This test was presented to an international participant pool of 19 medieval and early-music specialists who were asked to separately score the amount of reverberation as well as its suitability of the acoustics for each genre. Although opinions on reverberation were consistent with earlier experiments, assessments of acoustic suitability varied widely. Another round of the experiment is planned to gather more participant data for further analysis.

The methods of auralization hold great promise for this kind of interdisciplinary research where scientists and sociologists, historians, or musicologists collaborate. When asked to provide oral feedback on their experience, members of the ensembles commented on the plausibility of the interactive system, noting that they had similar issues performing within the re-created cathedral acoustics as they do within physical cathedrals. However, the early results also underline another key point: no matter how sophisticated the experiments, they are nevertheless conducted with the cooperation of modern participants. This introduces a new research question at the heart of the ongoing experiments surrounding the School of Notre-Dame: as musical styles and expectations change around us, what effect will they have on our taste and expectation for the acoustics we experience them in?

Public Mediation

Our research on Notre-Dame Cathedral's acoustics has spurred innovative projects aimed at highlighting its cultural significance. Virtual tours and audio productions like *Ghost Orchestra* offer immersive experiences of Notre-Dame's acoustic environment, showcasing its spatial variability (Katz et al., 2016; Postma et al., 2016). An extended audio-only version, offering an entire concert from several fixed positions, was produced during the Covid lockdown (see lavierge2020.pasthasears.eu) (Katz et al., 2021). Additionally, *Looking for Notre-Dame*, a radio fiction series, provides a three-dimensional (3D) sound experience, transporting listeners to explore the Cathedral's medieval essence through the mind of Victor Hugo (see bit.ly/49rKwwr; audio teaser: on.soundcloud.com/3HsPz) (Cros et al., 2022). The *Notre-Dame Whispers* audio-guide mobile app offers an immersive experience using binaural 3D audio narratives, covering various aspects of the cathedral's sonic history for visitors in multiple languages (see t.ly/QqN55 [Android]; t.ly/Abwfr [iOS]) (Muynke and Peichert, 2023).

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Origins and Acoustics of the Modern Pedal Harp

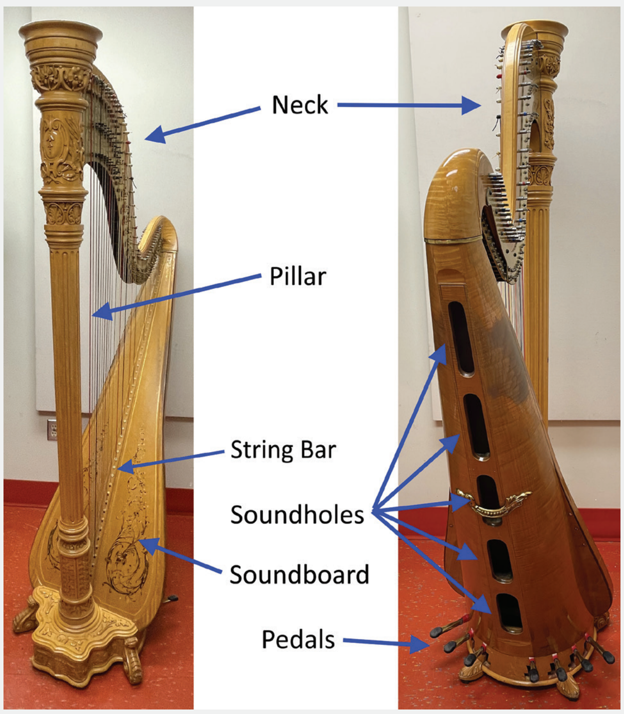
Chris Waltham

Introduction

Everyone knows what a harp looks like, at least at a distance, and what it sounds like, but few of us have had the chance to get up close and personal with the instrument and to appreciate its complexity and subtleties. Formally, harps are plucked string instruments with many strings arranged in a plane that is perpendicular to that of its soundboard (**Figure 1**). This geometry distinguishes harps from other many-stringed instruments like zithers and lyres, whose strings lie parallel to the soundboard.

Harps have a history going back to at least ancient Egyptian times, and today harps exist in many forms, the most technologically sophisticated of which is the pedal harp, the topic of this article. I concentrate on the pedal harp because it is the harp that concertgoers are most likely to encounter, and it encompasses all the features found in smaller, simpler harps. A general view of the modern pedal harp is shown in **Figure 1**.

Figure 1. *Two views of a pedal harp (Lyon and Healy model 23) showing its basic features. Photographs by C. Waltham.*



A few years ago, I worked with a University of British Columbia (UBC) Vancouver, British Columbia, Canada, music student, Katie Lee, to produce a five-minute video (see bit.ly/3SBGc7X) about the acoustics and mechanical engineering of a pedal harp. It was aimed at those who are not familiar with the instrument. The video takes the viewer on a tour around a pedal harp and ends with a demonstration of the vibrational behavior of the soundbox and a short piece of music played by Hayley Fahrenholtz (see bit.ly/3U2T5IW), who was also then a UBC music student. The images of pedal harps in this article are all of instruments owned by the UBC School of Music. All modern pedal harps have the same basic configuration and differ only in details.

The Anatomy of a Pedal Harp

Walk up to a pedal harp, by which I mean a large instrument of the type found in a symphony orchestra, and it is likely that the first thing you notice is the graceful curve of the neck (**Figure 2**).

The upper part of the neck is made of wood that is varnished or lacquered. Set in this wood is a row of tuning pegs (generally 47) that are turned to tune the strings. The lower part of the neck is faced with brass. In this part, the top row of fittings are the pins that define the vibrating length of each string at the lowest of three possible pitches. Below these are two rows of small *fourchettes* (two-pronged forks) that can be turned to grab a string, shortening its vibrating length to sharpen its

https://doi.org/10.1121/AT.2024.20.2.59

Figure 2. *Row of tuning pegs (**top**), string pins, and two sets of fourchettes (**bottom**) on the neck of a Salvi Aurora pedal harp. Photograph by C. Waltham.*

pitch by one or two semitones. If the fourchettes are not engaged, the strings are tuned to the pitch a semitone flatter than the white notes of a piano (the A string will play A♭). Engaging the upper fourchette brings the string up to natural pitch (the A string will play A♮). The lower fourchette will raise the pitch one more semitone (the A string will play A#).

Some of the strings are color coded to assist the harpist in finding the right ones. All the Cs are red and the Fs are blue. The lowest pitch strings are wire wound and thick. The highest pitch strings are thin nylon. In between are strings of traditional gut, a natural fiber typically made from sheep or goat intestines. The reason for the choice of gut over much cheaper nylon seems to lie in the way the elasticity of gut under tension differs from that of nylon and the way this difference allows for the production of higher harmonics in the middle pitch range (Woodhouse and Lynch-Aird, 2019). The bottom ends of the strings are connected to the soundboard (also called the table), which forms the front face of the soundbox (**Figure 1**). The string attachment points are reinforced with nylon plugs in the central string bar because the large tension, particularly on the lower strings, would rapidly pull the strings into the wood. The face of the soundboard is spruce with the grain running longitudinally and is often decorated. However, the inside of the soundbox, which can be seen through the soundholes in the back, is spruce with a *horizontal* grain (**Figure 3**).

The soundboard is made up of several parts. The most important parts acoustically are the horizontal slats, made of spruce, 30-80 mm wide, and glued together. These constitute the part of the structure that provides the optimum combination of strength, resonance, and sound radiativity. What you see from the front of the harp is a thin veneer, applied mostly for aesthetic reasons but also to add some additional strength to the soundboard against the outward pull of the strings (Firth and Bell, 1988). It is important to recognize that the total string tension on a harp such as this is on the order of 12 kilonewtons (kN), or over a ton in weight (Waltham, 2010). Thus, the designer of a harp soundbox must contend with two competing requirements: the soundbox must be light and mobile to radiate sound but stiff and strong to resist the string tension.

Moving down from the soundholes, we get to the pedals (**Figure 1**). These and their attendant linkages to the fourchettes are what allows the harpist to handle a change of key in the middle of a piece of music. Each pedal has

Figure 3. *View through a soundhole of a Lyon and Healy Concert Grand pedal harp. The vertical strip of wood down the center holds the string attachments.* ***Blue knot:*** *end of an F string;* ***red knot:*** *end of a C string. Photograph by C. Waltham.*

Figure 4. *A Lyon and Healy Concert Grand, with University of British Columbia (UBC), Vancouver, British Columbia, Canada, harp professor Elizabeth Volpé Bligh (see bit.ly/47N8OPx). Photograph by C. Waltham, with permission from Volpé Bligh.*

three possible positions: flat, natural, and sharp. The left-most pedal affects all the D strings, the next pedal to the right affects all the C strings, and so on, through B, E, F, G, and A. The pedals are connected, via a complicated mechanism, to the fourchettes on the neck (**Figure 2**).

The brass plates enclosing the linkages also add to the stiffness of the neck, which helps support it against the large twisting force from all the strings that are all connected on one side of the neck. Between the base and neck, the linkages must pass through the pillar of the harp (**Figure 1**), whose mechanical function is to support the neck against the combined tension of the strings.

Playing the Harp

Harp music is notated like piano music. During playing, the right hand handles the higher strings and the left, the lower. The top of the soundbox sits against the harpist's shoulder (**Figure 4**). The strings are plucked usually between a third and a half the way up from the soundboard. When appropriate, the strings may be plucked *près de la table*, meaning close to the soundboard to give a more extended spectrum. The strings can be plucked with the fleshy part of the fingers or, occasionally for a harder spectrum, with the nails. Because the strings vibrate for a long time, they frequently must be muffled to prevent short notes from blurring together, and there are many techniques for doing this (see bit.ly/48Y62Z2). It is also possible to play harmonics (in the musician's sense of the word) by gently touching the midpoint of the string with the base of the thumb and plucking the string with the thumb. The sound thus produced is ethereal (bit.ly/48C9RDk). Last, the soundbox may be used like a box drum and tapped, knocked, or slapped, producing a wide variety of sounds (see bit.ly/47HoGmC).

A Brief History

The earliest harps were of the "open" or "arch" variety. The frame was L-shaped, with the strings joining the necks and the soundboxes with no pillar to support the structure against the tension of the strings (**Figure 5**). Their sound tables were made of skin or wood (in the case of ancient Egypt, it is not clear which). Open harps continue to be played in various parts of the world and in particular in Africa (Fabre et al., 2023) and Southeast Asia (Williamson, 2010). The first frame harps (i.e., those with pillars) appeared briefly in classical Greece and Italy,

Figure 5. *Various configurations of open harps from Egypt. From Popular Science Monthly vol. 40, in the public domain via Wikimedia Commons.*

but this form was apparently forgotten until it reemerged in northwest Europe around 800 CE (Rensch, 2007).

In the last millennium, there have been three main areas of harp development: string materials, soundbox construction, and pitch-changing mechanisms. The first two tended to go together because better strings meant higher tension, which required stronger soundboxes. Harps need many strings to have a useable pitch range. Moreover, because of the attachment angle, the combined normal force on the soundboard can be enormous, and yet it must be flexible enough to radiate sound. Various sharping mechanisms were developed to be able to play harmonically more complex music without the number of strings proliferating (Rensch, 2007).

Early frame harps had soundboxes carved from single pieces of wood, particularly those from Ireland and the Scottish Highlands (Hadaway, 1980). Irish harps of this period were carved from logs of willow or yew. Strings were variously made of copper, bronze, brass, horsehair, silk, and gut (Firth, 1988). Tensions were low, as was the sound volume, which restricted the instrument to performance in small spaces.

Over the centuries, strings became stronger and more capable of withstanding higher tensions, and soundboxes evolved accordingly. The development of strong glues and improved cutting techniques allowed for the creation of thinner, stronger soundboxes, leading to the composite soundboards we see on pedal harps today.

A well-known example of a small German harp from the end of this early period (1700) is in the Boston Museum of Fine Arts (MFA), Boston, Massachusetts. The museum has published detailed plans of this harp, and I made a replica (**Figure 6**) and later published some of its vibroacoustic properties (Daltrop et al., 2012). This style of instrument is often referred to as "Gothic," the name being inspired by the shape of the neck.

Figure 6. *Replica of the Boston Museum of Fine Arts, Boston, Massachusetts, 1700 German harp made by C. Waltham. Photograph by C. Waltham.*

The instrument is entirely made of maple. It stands 130 cm high and has 36 strings. The lower strings are wrapped nylon and the upper strings are plain nylon. With a one-piece hardwood soundboard, this harp is a quiet instrument. Its pleasant tone can be heard in a sound clip on the Boston MFA website (see bit.ly/40ww42e) in which Nancy Hurrell is playing a replica made by Catherine Campbell of Port Townsend, Washington. However, as was common in this era, brays (**Figure 7**) were added to the soundboard at the string attachment points to boost the sound volume by buzzing against the vibrating string. The effect is an acquired taste (listen to historical harpist Bill Taylor playing a bray harp; available at bit.ly/40C4YXQ).

Figure 7. *Brays on the Waltham's replica of the German harp. The bray height can be lowered (by pushing into the soundboard) to make contact with the vibrating string. Photograph by C. Waltham.*

I have not engaged the brays on my harp (neither are they in the audio clip on the MFA site).

After 1700, more reliable glues and increasingly precise cutting techniques meant that soundboards could be made of multiple shorter pieces, with the wood grain running transversely, the better to withstand the string tension. These shorter pieces could also be made of resonant softwoods like spruce rather than stronger but stiffer hardwoods. As a result, brays disappeared. Music was changing, becoming more chromatic, and harps started appearing with multiple courses of strings, culminating in the Italian and Welsh triple harps of the eighteenth century (Firth, 1989). These harps had two outer courses of "white" notes, with a course of "black" notes in-between (see bit.ly/422eOTj). Apart from being ferociously difficult to play, this arrangement made yet more demands on the strength of the soundboard. Later, harp makers devised various means to allow semitone pitch changes, which allowed a smaller number of strings. In the latter half of the seventeenth century, harp makers in the Austrian Tyrol invented a manual hook mechanism that shortened the vibrating length of the string, raising the pitch a semitone (Rensch, 2007).

However, it was in France at the end of the eighteenth century that *pedal* harps emerged, allowing the sharping mechanism to be operated with the harpist's feet while music was being played (Rensch, 2007). The pedal mechanism developed through two intermediate phases, notably by Parisian makers Georges Cousineau (1733–1800) and François-Joseph Naderman (1781–1835). One was the *crochet* ("hook") in which the string was pulled against a stop. The second was the *béquille* ("crutch") in which two levers pressed on either side of the string. The form of pedal mechanism we see today is due to Strasbourg-born Parisian Sébastien Érard (1752-1831), who invented a device called the *fourchette* ("fork"), as described in **The Anatomy of the Pedal Harp**, where two "prongs" on a rotating disk grab the string. Ultimately, Érard added a second fourchette to each string, which could then be tuned flat. Érard patented this now ubiquitous "double-movement" seven-pedal action in 1810, and most modern pedal harps follow this pattern. (**Figure 8**).

The development of this instrument, whose construction requires precision wood and metalwork, had a lot in

Figure 8. *An 1828 Érard "double-movement" seven-pedal harp. The three positions available to each pedal can be seen at the base of the instrument, as described in* ***The Anatomy of the Pedal Harp.*** *Photograph by C. Waltham, from Kenwood House (Iveagh Bequest) owned by the English Heritage, London, United Kingdom, with permission.*

common with that of the piano, discussed in an earlier article in *Acoustics Today* (Giordano, 2016). Indeed, Érard was also famous for his pianos (Encyclopaedia Britannica, 2023). If the violin is a quintessential product of the Italian Baroque, the harp is a product of revolutionary France in the turbulent years between the end of the eighteenth century and start of the nineteenth. Érard had to cross the English Channel several times to evade the guillotine (he was uncomfortably close to Louis XVI and Marie Antoinette) and then the Continental Blockade. As a result, he set up manufactories in both Paris and London.

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Physics and Acoustics of the Harp

The Sound of a Harp

To my knowledge, there has been no formal blind study that shows whether listeners can distinguish the sound of a single plucked harp string, out of context, from that of any other string instrument of the same pitch. However, aspects of the harp's unique geometry and mode of playing suggest how we might be able to recognize its sound. First, harp strings are plucked close to their centers with the fleshy part of the finger, which produces a mellow sound with a spectrum that is stronger in the fundamental and a few low harmonics compared with, say, a guitar string plucked close the bridge, especially if done so with a plectrum (Le Carrou et al., 2007). Readers can compare the guitar with a pedal harp in a delightful sonata for both instruments by Alan Hovhaness (see bit.ly/48XiUOR). Second, unlike a piano, the rest of the strings of the harp are not damped and are strongly coupled to each other via the flexible soundboard. Thus, when you pluck a particular harp string, all the other harmonically related strings (i.e., octaves, fifths, fourths) will start vibrating. The result has been described picturesquely as a "halo of sound" (Le Carrou et al., 2009) that seems to envelope the instrument and is particularly noticeable as a harp is being tuned (see bit.ly/3O68dBA).

Third, and this is more technical and probably has a more subtle effect, the vibrating string does not simply energize the soundboard with small changes in its attachment angle as it vibrates, which is what happens in a guitar (Houtsma et al., 1975). Instead, the large angle the harp string makes to the soundboard means that changes in the *tension* of the string will also vibrate the soundboard (Waltham, 2010). The distinction is that the string tension changes as the string vibrates but with twice the fundamental frequency of the string, thereby enriching the sound spectrum (and causing some pitch glide). The effect is enhanced by the fact that the pluck amplitude can be large, only limited by the string spacing (about a dozen millimeters). One suspects that this effect is less obvious to the listener than the first two, but it is nonetheless demonstrably present (Woodhouse, 2022).

The Role of the Soundbox

The soundbox of the harp functions as all soundboxes do. Strings on their own do not vibrate enough air to make an appreciable sound, and so they are arranged to transmit their vibrations to a soundboard of much larger area, which then radiates the sound. Making a simple soundboard that will vibrate at the fundamental frequencies of the lowest harp strings would require a piece of wood much too thin to support the tension of the strings. This is also true of guitars and violins, even with the vastly smaller string tensions that these instruments must deal with. However, with the harp, the problem is acute. This is where the soundholes come in. The air in the hole vibrates against the air in the cavity and forms a coupled oscillator with the vibrations of the soundboard wood (Bell, 1997). Then, like all coupled oscillators, these two vibrations combine into two composite vibrations, one of lower frequency than either of the other two and one of higher frequency (Caldersmith, 1978). Although the soundholes allow the soundbox to radiate at a lower frequency than it would without them, harp strings go so low in pitch that a dozen or so of them have lower fundamentals than the soundbox can radiate (Daltrop et al., 2010).

unknown to nonharpists, who only wrote for the harp (see bit.ly/41YQF09). To single out one such composer, I recommend readers focus on the still living Bernard Andrès (1941–), who's haunting *Elegie Pour la Mort d'un Berger* features many of the playing techniques I have mentioned in ***The Sound of the Harp*** (see bit.ly/3SnLdAP).

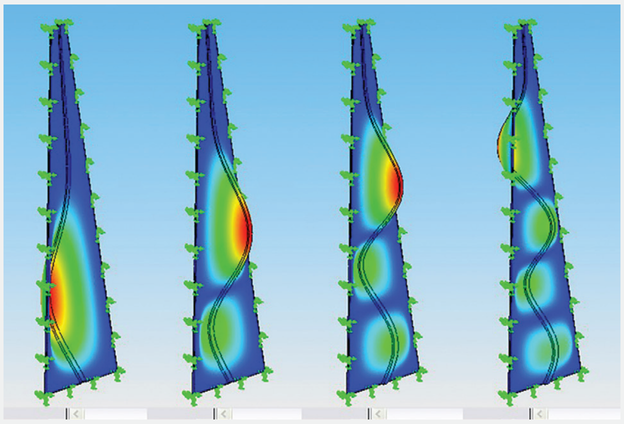

Figure 9. *First four vibration modes of a harp soundboard in a finite-element simulation. The lowest frequency mode is on the **left**. Figure by C. Waltham.*

Incidentally, this is also true for the G-string on a violin. The rest of the solution comes from the human ear and brain where, if we perceive enough higher harmonics, we mentally fill in the gap of the "missing fundamental" (Fletcher 1924) and do not notice its absence.

The Shape of the Soundboard

The trapezoidal shape of almost all harp soundboards can be explained with a simulation of the first few vibration modes of such a shape (see **Figure 9**). For the lowest frequency mode, the soundboard is vibrating at its wider (bass) end. For higher modes, the region of greatest vibration moves progressively up toward the treble end of the board. It would be nice if this progression in frequency could be matched to the pitches of the strings, but this is not possible because the board frequencies rise arithmetically (e.g., 1, 2, 3, 4), and the string frequencies rise geometrically (e.g., 1, 2, 4, 8). However, individual modes have a fair spread in frequency and strings have many frequencies (fundamental and harmonics) so the chance of a string being completely dead (unable to vibrate the soundboard at any of its frequencies at that particular attachment point) is small.

Harp Music

The pedal harp can handle a wide variety of musical styles, for example, jazz (see bit.ly/48XaPtE) or rock (see bit.ly/3HwTlsd). However, forgive me if I stick with the Western classical canon with which I am most familiar. Even narrowing the field like this, there is a large repertoire of solo harp music written by composers, mostly unknown to nonharpists, who only wrote for the harp (see bit.ly/41YQF09).

In the context of orchestral music, composers need to recognize that, like any plucked string instrument, the harp is quiet compared with bowed instruments. The loudest sound it can make is a glissando (see bit.ly/4bekuhx), and composers frequently use this as the auditory icing on the cake during a dramatic orchestral *tutti,* where everyone is playing at maximum volume. Otherwise, to give the harp prominence, the rest of the orchestra must quiet down. The harp cadenza at the start of the "Valse des Fleurs" from Tchaikovsky's *Nutcracker Suite* is a famous example (see bit.ly/3U48pF9). Harp concerti tend to work the best with a baroque orchestra (see bit.ly/47E5l5S) or, for more modern works, a chamber orchestra scored with a light touch (see bit.ly/3O8c29l).

Smaller Harps

Although full-size pedal harps tend to be alike in size and number of strings, differing largely in the style of decoration, smaller harps abound, often made by amateurs. In fact, for someone wishing to gain experience in instrument making, a small harp is probably the simplest and most satisfying project to start with. The complexities of a pedal

Figure 10. *Detail of sharping levers on a Celtic harp. Figure by E. Volpé Bligh, with permission.*

harp soundbox can be dispensed with and replaced with a box of thin, good-quality plywood. Small harps are known variously as folk harps, Celtic harps, or lap harps (for the smallest). If they have any sharping mechanism at all, it is with small levers mounted on the neck (**Figure 10**). These levers raise the string pitches by a semitone and are usually set at the beginning of a performance, although a dextrous harpist can effect changes midstream when needed by an accidental or a change of key. As with the members of the violin family, the smaller the soundbox, the higher the frequencies of sound radiated, and lever harps tend to have a lighter sound than the larger pedal harps (bit.ly/48UmRnw).

Conclusion

For readers not hitherto familiar with the pedal harp, I hope this article has given a taste of the instrument and its subtleties and complexities and thus increased the enjoyment of the music and respect for the talent of those who play it.

Acknowledgments

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About the Author

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Chris Waltham has been a professor at the University of British Columbia (UBC), Vancouver, British Colombia, Canada, since 1990. He has spent most of his research career in particle physics, notably with the Sudbury Neutrino Observatory project. More recently, he has worked in musical acoustics, specializing in Western and Chinese string instruments. He is currently semiretired, teaches in UBC's Science One program, and builds harps and violins. He is president of the British Columbia Violin Makers Association and plays second violin in Vancouver's Little Night Music Orchestra.

Recent Acoustical Society of America Awards and Prizes

Acoustics Today is pleased to present the names of the recipients of the various awards and prizes given out by the Acoustical Society of America. After the recipients are approved by the Executive Council of the Society at each semiannual meeting, their names are published in the next issue of *Acoustics Today*.

Congratulations to the following recipients of Acoustical Society of America medals, awards, prizes, and fellowships, who will be formally recognized at the Spring 2024 Plenary Session. For more information on the accolades, please see acousticalsociety.org/acoustical-society-of-america-awards, acousticalsociety.org/prizes, and acousticalsociety.org/fellowships-and-scholarships.

Gold Medal
Ingo R. Titze
(National Center for Voice and Speech, University of Utah, Salt Lake City) for contributions to understanding human voice production and the development of clinical applications

Helmholtz-Rayleigh Interdisciplinary Silver Medal in Biomedical Acoustics and Physical Acoustics
D. Keith Wilson
(US Army Engineer Research and Development Center, Hanover, New Hampshire) for contributions to atmospheric acoustics and computational acoustics including applications to national defense

William and Christine Hartmann Prize in Auditory Neuroscience
Christopher A. Shera
(University of Southern California, Los Angeles, California)

R. Bruce Lindsay Award
Christopher M. Kube
(Pennsylvania State University, State College) for contributions to the understanding of ultrasonic propagation and nonlinearity in polycrystalline materials

Medwin Prize in Acoustical Oceanography
Julien Bonnel
(Woods Hole Oceanographic Institution, Woods Hole, Massachusetts) for contributions to signal processing with applications in acoustical oceanography and bioacoustics

Congratulations also to the following members who were elected Fellows in the Acoustical Society of America in Fall 2023.

- **Ahmad T. Abawi**
(HLS Research Inc., La Jolla, California) for contributions to modeling underwater sound propagation and scattering
- **W. C. Kirkpatrick Alberts II**
(DEVCOM-Army Research Laboratory, Adelphi, Maryland) for contributions to tactical infrasound and battlefield acoustics
- **Simone Baumann-Pickering**
(Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California) for contributions to passive acoustic monitoring of beaked whales
- **Ana M. Jaramillo**
(Olson Sound Design, Brooklyn Park, Minnesota) for service to the Society, outreach to Spanish speakers, and acoustics education
- **Jungmee Lee**
(University of South Florida, Tampa) for contributions to auditory processing of simple and complex signals
- **Michael L. Oelze**
(University of Illinois Urbana-Champaign, Urbana) for contributions to quantitative ultrasound tissue characterization

Conversation with a Colleague: Eleanor Stride

Eleanor Stride
Conversation with a Colleague Editor: Micheal L. Dent

Meet Eleanor Stride

Eleanor Stride is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague." Eleanor is currently a professor of bioengineering at Oxford University, United Kingdom, specializing in stimuli-responsive drug delivery. She obtained her BEng and PhD from University College London (UCL), United Kingdom, before moving to Oxford in 2011. She has over 200 publications and 12 patents and is a director of two spin-out companies set up to translate her research into clinical practice. She is a Fellow of the Acoustical Society of America (ASA), The Institute of Engineering and Technology (IET), and the Royal Academy of Engineering. She was elected as an Honorary Fellow of the Electrical Research Association (ERA) Foundation for contributions to public engagement. She received the ASA Bruce Lindsay Award and the IET A. F. Harvey Prize, was nominated as 1 of the 100 most influential women in engineering in 2019, and was made an Officer of the Order of the British Empire in 2021. Outside of work, she is a passionate dancer and teaches Lindy Hop and other swing dances. We asked Eleanor 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.

There have been amazing advances in the development of new drugs over the twentieth and twenty-first centuries, yet millions of people still die every year from heart disease, cancer, and infection. There are many reasons for this, but one important factor is that there has been surprisingly little attention given as to how the drugs are delivered. Most drugs are given by mouth or by injection. The problem with that is that they go everywhere in the body and a very small percentage goes to the disease site. The rest is at best flushed out of the body and at worst leads to major side effects. The aim of my research is to try to tackle this lack of accurate targeting. My team are therefore developing ultrasound-responsive micro- and nanoparticles to encapsulate drugs so that they don't interact with tissue until they reach the target site. We try to get as many particles as possible in the target region, for example, by making the particles magnetic or attaching molecules to their surfaces that bind to particular types of cells. We then use a short burst of ultrasound focused on the target region to trigger the release of the drug.

What inspired you to work in this area of scholarship?

The short answer is a series of lucky coincidences. I pursued a very mixed set of subjects at my high school in London: mathematics, physics, and chemistry together with Latin, art, and general studies. I was always much happier solving mathematics and physics problems than writing essays, but I did also much enjoy the opportunities for independence and creativity offered by art. It was actually art that led me to engineering. When I was 16, my art teacher took me to the end-of-year exhibition by postgraduate students on the industrial design course at the Royal College of Art in London. Seeing the amazing work on display made me determined to pursue a career as an industrial design engineer, and three years later I enrolled as an undergraduate in mechanical engineering at UCL. After university, I intended to take a postgraduate course in industrial design. During the

https://doi.org/10.1121/AT.2024.20.2.68

final year of my degree, however, I worked on a research project developing an experimental rig and software for imaging inside an oil pipe using ultrasound. I very much enjoyed the project and also became fascinated with ultrasound physics. A serendipitous meeting with a senior radiologist at UCL Hospitals then introduced me to the amazing properties of microbubbles and their potential use in both ultrasound imaging and therapy. It was this that led me to pursue my PhD and subsequently a research fellowship. I have been playing with bubbles and other types of particles ever since.

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

That is a very hard question to answer because almost everything in my research is linked to something else, so picking out just one bit is very difficult. Also, almost of my work is collaborative and involves lots of people from different disciplines. Thus, I never really feel that anything is "mine." It is always my team's contribution. I am still very excited by a project that I started during my research fellowship on creating magnetic microbubbles. I still remember when I first saw the magnetic bubbles move under the microscope when I brought a magnet close to them. I could not believe that the idea had actually worked.

I was even more excited to subsequently collaborate with a cancer biologist to see if we could use the magnetic bubbles to increase the efficiency of ultrasound-mediated gene transfer. It had already been shown in the literature that exposing cells to microbubbles and ultrasound in the presence of DNA could push DNA into the cells. The cells would then express the relevant gene. The efficiency of the transfer process was, however, very low. Our idea was to place a magnet under the lower surface of the plate on which the cells were growing. The magnet would pull the magnetic bubbles down toward the cells and this would increase the probability of a microbubble being in contact with a cell membrane when we turned on the ultrasound. Hence the probability of the bubble being able to transfer DNA into the cell would hopefully increase. The experiments did not get off to a great start. It was my first experience of working with cells, and on the first go I managed to kill everything. I was so worried about keeping everything sterile that I used double-distilled water instead of saline, thinking it would be "cleaner," but, unfortunately, distilled water is lethal for cells. Luckily, things went a lot better after that, and we saw a fourfold increase in gene expression with the magnetic bubbles compared with a commercial microbubble agent.

That project has evolved considerably and, in addition to improving the microbubble formulation substantially, we have developed a new type of ultrasound probe that incorporates a magnetic array so we can do simultaneous imaging and targeted therapy (for more on this, please see bit.ly/AT-Gray). We have had some very promising results in both cancer models and for delivering anticlotting agents for stroke therapy. Yet it has been challenging to move the technology toward clinical application because it is such a big change compared with current procedures, but we are getting there slowly.

Another extremely exciting moment was the first time we saw a beneficial effect in a human volunteer. This was for a study using bubbles to try to boost oxygen levels in tissue. I was absolutely terrified something might go wrong, even though we had tested everything very carefully in the laboratory, including in mice, and I had even taken some of the oxygen bubbles myself just to be sure. When we saw the oxygen levels go up in the first volunteer and there were no side effects, we were all jumping around in excitement. We have gone on to do three more studies in humans. Two of these have been in sets of healthy volunteers, and one in a group of patients. So far, the results have been encouraging, and we are hoping this will enable us to develop new treatments for a range of conditions including lung disease and cancer.

If I do have to pick one contribution, then I would probably choose our work on cancer. One of the reasons for developing the oxygen bubbles is that many cancerous tumors have very low levels of dissolved oxygen and that makes them very resistant to almost every type of treatment. My colleagues John Callan and Tony McHale at Ulster University in Northern Ireland have been working on a novel type of therapy using ultrasound-activated drugs to treat pancreatic cancer. Unfortunately, these drugs are very ineffective in the absence of oxygen. John and Tony approached me at a conference to ask if it was possible to tag their drugs onto oxygen-loaded bubbles, and the project grew from there. We have now taken the bubbles into production in a clean room facility and are hoping to run our first clinical trial next year. Pancreatic cancer remains one of the most lethal forms of cancer, and survival rates have not improved since the 1960s. We are hoping that we will be able to change that. The project has also led to some extremely interesting fundamental science on the mechanisms by which the drugs are activated by ultrasound. These mechanisms are very far from understood.

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

Something I have started to care about enormously as I have gone further in my career is public engagement. I get very upset when I hear colleagues dismissing public engagement as "soft" and not real work. There is a terrible problem with a lack of understanding and hence a lack of trust of science and technology among the general public and, sadly, also among politicians and journalists. An obvious example is the resistance to vaccination that became so acute during the Covid-19 pandemic. I find this very bizarre and distressing because most people's lives are dependent on technology in some form or another. I think it is vital that scientists and engineers do everything we can to combat that lack of trust in science and to do that, we need to communicate regularly, clearly, and honestly about what we do, including the many things we just do not know. I have contributed to quite a few TV and radio programs and also several podcasts and videos (see bit.ly/CWC-Stride1; bit.ly/CWC-Stride2; bit.ly/CwC-Stride4; bit.ly/CwC-Stride5; bit.ly/CwC-Stride6). Initially, I was absolutely amazed that anyone downloaded them, but the feedback has been great, particularly from high-school students. Indeed, I was at an event recently and a lady came up to me and said: "You don't know me, but our physics teacher showed us your video at school and that's why I did physics at university and am now doing a PhD." Possibly the most important and humbling engagement I am involved in is working with patient groups. I think that understanding what they are experiencing and what they value and need is absolutely vital if one is working in biomedical engineering.

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

My immediate priorities are the work we are doing on cancer and also our using microbubbles for the delivery of antibiotics to treat drug-resistant infection. We are hoping to run clinical studies in both these applications in the near future. There are, however, many interesting questions in terms of the fundamental science that my team is working on as well. It's becoming increasingly evident that when we use ultrasound and bubbles to deliver drugs in one part of the body that we are also triggering system-wide effects, in particular an immune response. Understanding that and how we can control it is crucial to ensure patient safety. It is also potentially a response that could be usefully exploited such as to prevent cancer from coming back after therapy.

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International Student Challenge Problem in Acoustic Signal Processing 2024

Brian G. Ferguson, R. Lee Culver, and Kay L. Gemba

An initiative of the Acoustical Society of America (ASA) Technical Committee on Signal Processing in Acoustics (TCSPA) is to pose international student challenge problems in the discipline of acoustic signal processing (Ferguson and Culver, 2014; Ferguson et al., 2019, 2023). At the 185th meeting of the ASA (December 4-8, 2023, in Sydney, Australia), the TCSPA proposed posing a problem for 2024 on the localization of free-ranging echolocating dolphins that would appeal not only to acoustic signal processors but also to a broader group of students such as marine bioacousticians.

The International Student Challenge Problem for 2024 involves the student (or team of students) processing real acoustic data to extract information about sources from the sounds that they project. Specifically, the sources of sound are free-ranging echolocating dolphins, where students have the opportunity to address aspects of Au's observation (1993, p. 271): "Our perception of how dolphins utilize their sonar in the wild is based on extrapolation of knowledge observed in 'laboratory' experiments — we do not have the foggiest idea of how dolphins utilize their sonar in a natural environment."

For the present problem, the acoustic sensors are three hydrophones (H1, H2, and H3) located 1 m above the sea floor in water 20 m deep. The hydrophones are distributed along a straight line, with a separation distance of 14 m between adjacent hydrophones (i.e., the uniform interelement spacing of the three-element horizontal line array is 14 m). Hydrophone H2 (the middle sensor) is at the center of the array and is referred to as the reference hydrophone located at the origin. The array axis, which extends from H1 to H3, is oriented in a west-east direction, i.e., H1 is to the west of H2 (the origin), and H3 is to the east. The hydrophone outputs are all sampled for 8.2 s at the rate of 250,000 samples/s (i.e., the sampling period is 4 μs). The digital time series of sampled data for each hydrophone is recorded in Waveform Audio File Format (WAV). The element-level data files are HYD1.wav, HYD2.wav, and HYD3.wav, and they can be downloaded as .wav files at acousticstoday.org/asa-student-challenge-2024.

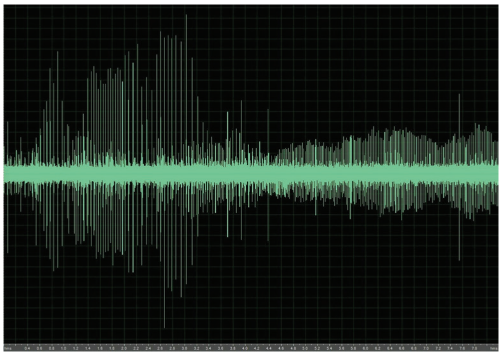

Figure 1. *Variation with time of the output of the middle hydrophone: H2.*

Task 1

The variation with time of the output of H2 (HYD2.wav) is shown in **Figure 1**. Two sequences (or trains) of dolphin echolocation clicks are evident: one sequence starts near the beginning (emitted by dolphin A) and the other (by dolphin B) starts near the middle. Other extraneous impulses observed in the data file can, in the main, be attributed to the snaps of shrimp. The first task is to detect the echolocation clicks and record the time of arrival (TOA) of the peak pressure (maximum amplitude) of each click at H2 for click sequence A emitted by dolphin A and then repeat for click sequence B.

(1) In microseconds, what is the uncertainty in your TOA measurement of a click's maximum amplitude (or peak pressure)?

(2) For each click sequence, plot the variation with click number of the interclick interval (ICI), i.e., the time difference of arrival of consecutive clicks or the time interval (time span) between successive click peak pressures. Calculate the mean and standard deviation

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of the ICI for each click sequence along with the total number of clicks (*N*).

(3) For technological sonars, the pulse repetition frequency is constant, i.e., the time interval between sonar pulse transmissions is constant. Is this the case for the echolocation biosonars of dolphins A and B?

Task 2

The next task involves locating the positions of the sources of the clicks, i.e., localizing the sound projectors of the echolocating dolphins. This task requires associating each click received on H2 with its counterparts in the sequences received on the adjacent hydrophones H1 and H3. Intuitively, the *difference* in a click's arrival times, i.e., the differential time of arrival (DTOA), at a pair of hydrophones has directional information. For instance, when the DTOA is zero, (i.e., the TOAs are the same), the source is in a broadside direction (i.e., at right angles to the array axis). Similarly, for a pair of adjacent hydrophones separated by a distance $d = 14$ m, if the DTOA has a maximum value of $+{}^{d}/_{c} = {}^{14}/_{1520} \approx 9.2$ ms (where $c = 1520$ m/s is the isospeed of sound travel in the underwater medium for the present experiment and 'ms' denotes milliseconds), then the source is in an end-fire direction (i.e., in the direction of the array axis). When the DTOA has a minimum value of $-{}^{d}/_{c}$, the source is in the other end-fire direction. The source bearing (β) is measured in a counterclockwise direction with respect to the (east-west) array axis, e.g., $\beta = 0°$ is due east and $\beta = 90°$ is due north. Whereas only one pair of hydrophones is required to estimate the source bearing (i.e., the angle of the source relative to the array axis), two adjacent pairs are required to estimate the source range. The range (*R*) is measured with respect to the origin, i.e., the position of the middle hydrophone H2.

(1) For dolphin A, plot the variation with click number of the source bearing. Calculate the mean and standard deviation of dolphin A's bearing estimates for the echolocation click sequence along with the total number of clicks (*N*). Repeat for dolphin B. Comment on how well your estimates localize the direction of each echolocating dolphin. Do your bearing estimates indicate that the source is in motion? Are you able to estimate the *precision* of your bearing estimation method, where the term *precision* is used to indicate the closeness with which the measurements agree with one another quite independently of any systematic error involved; the precision is limited by random errors and excludes any systematic (or bias) errors.

(2) For dolphin A, plot the variation with click number of source range. Calculate the mean and standard deviation of dolphin A's range estimates for the echolocation click sequence along with the total number of clicks (*N*). Repeat for dolphin B. Comment on how well your estimates localize the range of each echolocating dolphin.

Your solution should detail your approach, signal-processing methods, and reasoning to solve the problem as well as your best estimates for the above parameters.

The deadline for student submissions is November 15, 2024. Submit your solutions along with your contact details and proof of student status to asa@aip.org with the subject line Entry for International Student Challenge Problem in Acoustic Signal Processing 2024.The finalists and prize winners (monetary prizes for winning entries: first place, \$600; second, \$400; and third, \$300) will be announced by November 30, 2024.

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Explore Acoustics Through ASA Publications' Podcasts

Kat Setzer

Whenever I mention the Acoustical Society of America (ASA) publication's podcast, *Across Acoustics* (acrossacoustics.buzzsprout.com), to someone in the Society, I usually get one of two responses: "I love it!" or "ASA has a podcast?" Sadly, the latter response is still all too common, even though we have published over 50 episodes and have surpassed 20,000 downloads. Thus, my goal with this article is to introduce more people to my pet project. Hopefully, you will enjoy listening to it as much as I have enjoyed recording it!

Across Acoustics started in 2021 and currently publishes two episodes per month. The podcast covers material from all four of the ASA's publications: *The Journal of the Acoustical Society of America* (*JASA*), *JASA Express Letters* (*JASA-EL*), *Proceedings of Meetings on Acoustics* (*POMA*), and, of course, *Acoustics Today* (*AT*). Guests on the show have included ASA Gold Medal winners, student researchers, *JASA* guest editors, and other members of the acoustics community representing research institutions and other organizations all over the world. Our aim is to share interviews that are easy to understand, even if the research is not in your field, so you can find out more about what's happening in the world of microphones, supersonic jets, common shrews, lung ultrasound, or any of the many topics covered in our publications. And much like with articles in *AT*, we hope that the podcast content will be appealing and accessible to those outside of the Society as well, so you can share with the nonacousticians in your life!

Below are some of our most listened-to episodes, representing the diversity of topics that we cover on the show. I have also included QR codes for readers who would prefer to listen to episodes on their mobile devices. The next time you are driving to work or doing chores around the house, pop on one of these episodes to make your experience a bit more fun and educational!

What Is Silence?

This highly downloaded episode (see bit.ly/AA-silence) takes a bit of a philosophical bent and will likely appeal to most folks who are interested in the study of sound. In it, ASA Gold Medal recipient William Yost (Arizona State University, Tempe) talks about how we define sound, how perception impacts our understanding of sound, and whether silence is simply the absence of sound or something else.

What Is an Acoustic Metamaterial?

Metamaterials have been a hot topic in the acoustics community since the late 1990s (see bit.ly/4bgmUvv), but there's no consensus among researchers as to what a metamaterial actually is or when they first came about. Christina Naify (University of Texas at Austin), chair of the Structural Acoustics and Vibration Technical Committee, took a deep dive into the literature about metamaterials and then posed the question to an audience of researchers in a session at the ASA conference in Chicago, IL. In this episode (see bit.ly/aa-acoustic-metamaterials), we talk about what came up in that discussion.

Deep Faking Room Impulse Responses

It's not always feasible to measure the entirety of a sound field. Instead, scientists use models to come up with a best guess of the missing pieces. In this episode (see bit.ly/AA-room-impulse-responses), we talk with Efren Fernandez-Grande and Xenofon Karakonstantis (Technical University of Denmark, Kongens Lyngby) about their new machine learning method to reconstruct sound fields.

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Conservation Bioacoustics: Listening to the Heartbeat of the Earth

Recent advances in technology have allowed scientists to gather larger quantities of acoustic data from locations more remote than ever before. As a result, the study of animal sounds can be used to inform species or habitat conservation and natural resource management practices in new and exciting ways. In this episode (see bit.ly/AA-cons-bioacoustics), we talk to Aaron Rice (Cornell University, Ithaca, New York) about how acoustics can be used to advance conservation efforts as well as how people outside large research universities can take part in efforts to help save the planet with science. (This episode stems from an article Rice wrote for *AT* (see doi.org/10.1121/AT.2023.19.3.46).

Modeling of Musical Instruments

How does a piano string compare to an ideal physicist's string? Are there equations that describe the sound a recorder produces? Can the quality of an instrument be quantified? In this episode (see bit.ly/AA-modeling-instruments), we talk to one of the editors of the *JASA* Special Issue on Modeling of Musical Instruments (see bit.ly/4as4RkD), Nicholas Giardano (Auburn University, Auburn, Alabama), about the wide variety of research efforts regarding analytical and computational techniques to model musical instruments, and how these techniques can help both instrument makers and musicians.

Reconsidering Classic Ideas in Speech Communication

Most researchers know the seminal articles that have impacted their field. Sometimes, though, the research in those articles can get misinterpreted or exaggerated, and those misunderstandings can take hold and reappear year after year. In this episode (see bit.ly/AA-speech-comm), we talk to the editors of the *JASA* Special Issue on Reconsidering Classic Ideas in Speech Communication (see bit.ly/4arfzrJ), Matthew Winn (University of Minnesota, Minneapolis), Richard Wright (University of Washington, Seattle), and Benjamin Tucker (Northern Arizona University, Flagstaff), about ideas in speech communication that were reexamined in the Special Issue.

This is only a handful of our many episodes, which span the breadth of the ASA's areas of study. I hope after listening to some of these, you will be enticed to explore our archives and find more that pique your interest! Plus, the podcast is available on the major podcast platforms, so you can subscribe and have the latest episode delivered directly to your mobile device.

And more good news: Going forward, *AT* will be including links to related episodes with every article (and QR codes, so you can just scan with your phone and listen!). Keep an eye out for insets with related content in the articles of this and coming issues of *AT*.

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