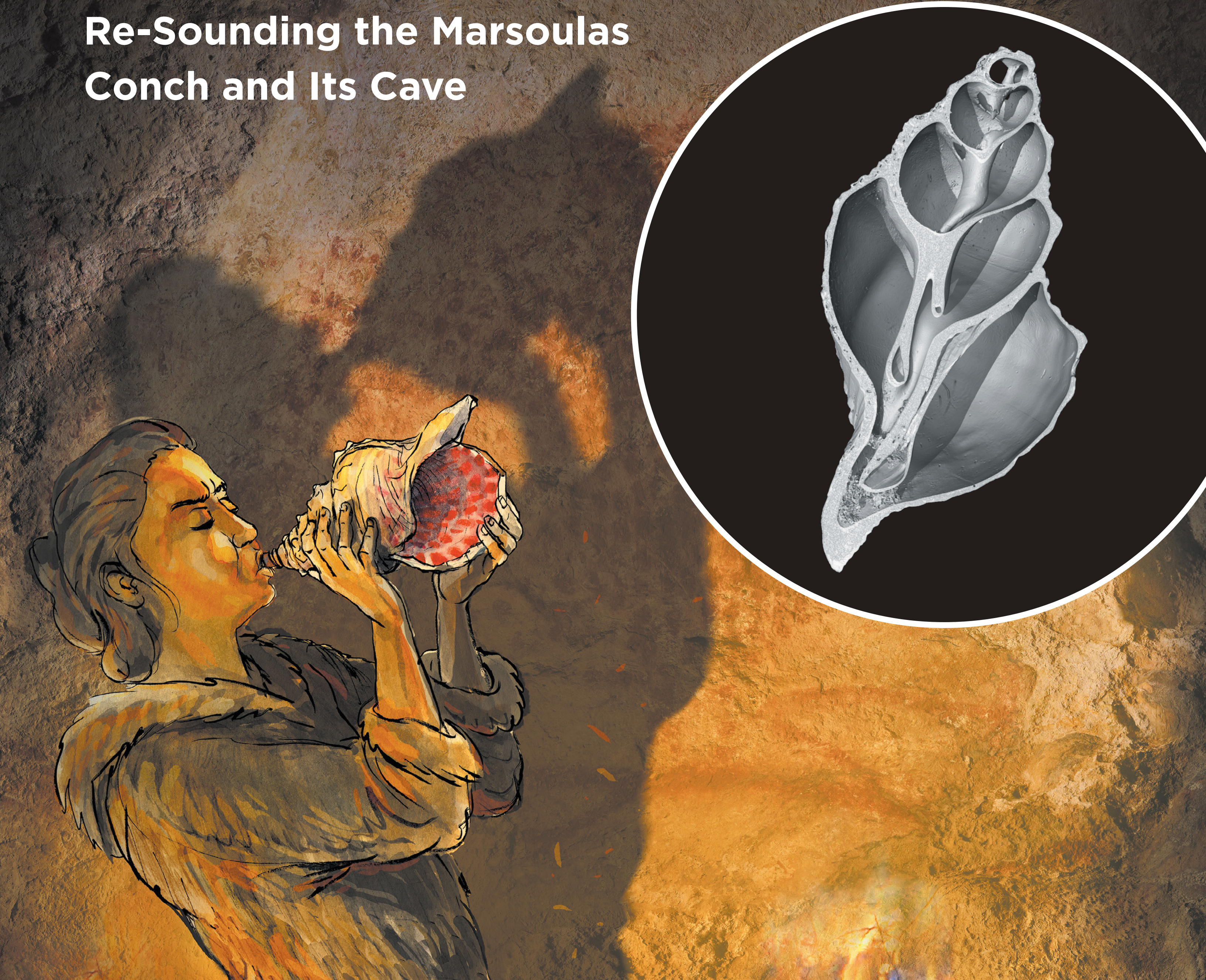
Acoustics Today

Summer 2022 Volume 18, Issue 2

ASA ACOUSTICAL SOCIETY OF AMERICA

An Acoustical Society of America publication

Acoustics in Music Archaeology: Re-Sounding the Marsoulas Conch and Its Cave



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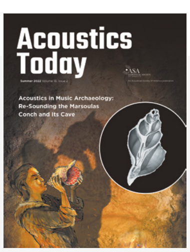
Featured Articles

Sound Perspectives

Departments



About the Cover

Cover image from article by Kolar et al. (page 52). Drawing of Marsoulas cave and conch performance by Gilles Tosello, with inset cross-section of the archaeological *Charonia lampas* shell from 3D model capture by Carole Fritz. Figures reproduced by permission of Carole Fritz and Gilles Tosello.

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www.acousticalsociety.org

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From the Editor

Arthur N. Popper

This issue of *Acoustics Today* (*AT*) introduces a new series of "Sound Perspectives" essays, "Conversation with a Colleague" (CwC). Edited by *AT* Associate Editor Micheal Dent, CwC focuses on mid- and senior-career Acoustical Society of America (ASA) members who have made a substantial contribution to their field. The individuals may be from academia, industry, and/or government.

The purpose of CwC is to introduce the broad ASA audience to leaders in acoustics and to teach about diverse areas of the discipline. CwC essays will be shorter and much more informal than articles in *AT*. Most importantly, and unlike regular articles, the essays will focus on the contributions of a single person rather than on a broader field. We also want to "drive" CwC essays to have roughly the same information, and so our colleagues will be asked to answer a specific set of "prompts" in their responses.

We plan on one essay for each issue of *AT*, with the goal of representing each technical committee (TC) at least once in the next three years. To do this, we will invite each TC to nominate two or three people as potential participants in the series. The individual will be selected by the *AT* editor and associate editor, with a focus on topics that, hopefully, will be of interest to the broad ASA membership.

Normally, I do not discuss our regular "From the President" article, but I do want to remind readers to look at it and also a special "Sound Perspectives" essay by ASA Executive Director Susan E. Fox. In her last column as president of the ASA, Maureen Stone talks about some of the history of the ASA and ties it nicely to its future. As part of the essay, Maureen shares several links to the first issue of *The Journal of the Acoustical Society of America* (*JASA*). This is great fun to look at!

In the first article, Mitra Aliabouzar and Mario Fabiilli discuss the healing of wounds and how bubbles can be used to help build tissues in the body. They demonstrate that these bubbles, which are used for building new blood vessels, can be controlled using ultrasound, giving us another way in which ultrasound is used in biomedical applications. (For additional biomedical applications of ultrasound, see "*AT* Collections" at tinyurl.com/mtmturra.)

The second article by Daniel Butko focuses on education in acoustics, with a discussion of the approaches he uses in teaching architectural acoustics. Dan's approaches are quite interesting, and they should be of value to for teaching most any STEM subject. Thus, I encourage everyone who teaches, both formally or informally, to take a look at this article.

The next article is by Erin Fischell who shares insight into how one might get "weird" data when doing underwater acoustic sensing. Erin makes it clear that one cannot just accept data as recorded but that it is imperative to be very careful in interpreting and understanding the data. Indeed, although the article focuses on underwater sound, the broader message is that no matter how we record data, it is important to ensure that there are no artifacts and that any artifacts are very well hidden and hard to figure out. (For other *AT* articles on underwater acoustics, see "*AT* Collections" at tinyurl.com/exppd4fd.)

I was quite surprised, in reading the fourth article by Susanne Fuchs and Aleksandra Ćwiek, that there are well over 4,000 extant languages. They share this information in the context of talking about relationships between language sounds and meaning. They also consider the evolution of language and make a case that vocal sounds are related to information about the meaning of the sounds from other sensory stimuli such as vision. (*AT* has many articles on language; see tinyurl.com/2p8rmdxz.)

Our fifth article, by Miriam A. Kolar, Carole Fritz, and Gilles Tosello, discusses music archaeology by focusing on the sounds from an 18,000-year-old conch shell that was found in a French cave. The authors share how they worked out that the shell is a musical instrument, and they discuss the relationships between the sounds of ancient instruments and the acoustics of the caves in which they have been found. (For more articles about archaeology and acoustics, see our "*AT* Collections" at tinyurl.com/4tcpf9ez.)

The final article by Barry B. Ma, Brian D. Dushaw, and Bruce M. Howe comes back to ocean noise, discussed in this issue in the article by Erin Fischell. The article by Ma et al. discusses measuring the rainfall at sea. Before reading the article, I had never really thought about the value of rainfall over the oceans in understanding weather, and I certainly had no idea how rain would be measured when very far from shore.

The three "Sound Perspectives" essays are of real interest. The first one is the CwC essay by Joseph A. Sisneros at the University of Washington, Seattle. Joe is a member of the Animal Bioacoustics TC and does research in the general area of fish bioacoustics. To be fully open, Joe is a collaborator of mine, and it was therefore pretty easy to get him to be a "guinea pig" and work with Micheal and I as we developed the format and style for this series.

The second essay is by Susan E. Fox, executive director of the ASA. Susan starts her essay with a quote by one of the most famous doctors of all time, Theodor Seuss Geisel (aka Dr. Seuss). She uses this quote as the context in which to talk about some of the challenges that have been facing the ASA over the past years and outlines challenges to the ASA (and most all societies) for the near future. This, combined with Maureen's essay, provide considerable food for thought for all ASA members, and I urge every member to read, and think about, the issues raised.

The third essay by Kathi Mestayer, Andrew Morrison, and Edward Richards focuses on social media and its use in acoustics. I readily admit that I have almost no knowledge of, or interest in, social media. Yet I have to admit that the authors, all members of the ASA Publications ad hoc social media Engagement Advisory Board, make a great case, even to me, as to how social media can enhance one's work and help communicate not only with colleagues but also with a broader audience.

Finally, I want to share a picture of the two newest members of the ASA Publications family, both of whom have already discovered the value of reading *AT*. The young men are the sons of two people that are so very instrumental in making *AT* (and all of ASA publications) so excellent, Kat Setzer and Liz Bury.

Maureen Stone

The Past Is Prologue

June 2022 was the 182nd meeting of the Acoustical Society of America (ASA) and its 93rd year of existence. We are approaching our Centenary Celebration in 2029. So, this is a fitting time to look back at the Society's history and think about its future.

In September 1928, Wallace Waterfall began writing colleagues to start a society of Architectural Acousticians.

> "Within the last few years there have been a great many developments in the subject of architectural acoustics. Architects, builders, and the public in general are beginning to recognize in the building industry a new engineering science which is approaching a state of development comparable with other engineering sciences... The thought of some organization such as a Society of Acoustical Engineers immediately suggests itself... It is realized that if the society is really to be successful in promoting the interests of Architectural Acoustics and the industry which has developed around this subject, it must be organized on a highly scientific basis and be kept free from reproach in all its activities" (from a letter by Wallace Waterfall, October 10, 1928, to a group of individuals from universities, Bell Telephone Laboratories, Riverbank Laboratories, and the Bureau of Standards).

Waterfall was persuaded to open the Society to other fields, so that by December 1928 a group met to write a constitution and bylaws, which were approved at the first business meeting of the ASA on May 10, 1929. The minutes of this meeting were published in the first issue of *The Journal of the Acoustical Society of America* (*JASA*) (asa.scitation.org/toc/jas/1/1) in October 1929 (**Figures 1** and **2**).

The Society was founded by individuals from universities and employees of companies such as Bell Telephone Laboratories, AT&T, CG Khan music, movie studios, and others, all of whom needed research published that was relevant to them. Full membership in the ASA was limited to those who were doing experimental work on the subject of acoustics. Associate membership was aimed more at companies and those interested in the sales end of the work.

Their motivation for starting this new journal and the Society was the increase in new science in the field of acoustics. These companies needed the ASA, and many of them became sustaining members to support the Society. There was no government funding or intervention in research at that time. Waterfall felt that "the organization...must be on a very high plane...commercialism must be held strictly in the background, or we could not expect the support of those true scientists whose membership is essential to the Society's welfare" (from a letter by Waterfall on September 27, 1928, to Armin Elmendorf, consulting engineer for the Celotex Corporation).

However, lack of commercialism did not mean lack of participation by employees of private companies. On the contrary, for many years, membership of the Society was composed of employees of private companies and some universities (see **Table 1**).

Shortly after the founding of the ASA and the publication of the first issue of *JASA*, the stock market crashed

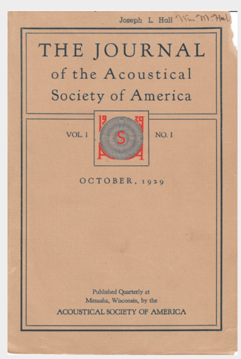
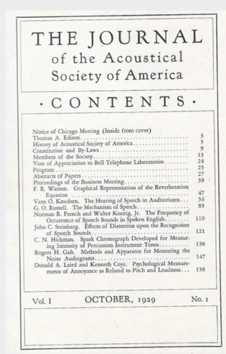


Figure 1. *Cover of the first issue of* The Journal of the Acoustical Society of America (JASA)*. This issue is free access and can be found at* asa.scitation.org/toc/jas/1/1.



THE JOURNAL
of the Acoustical
Society of America

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Figure 2. *Table of Contents of the first issue of* JASA.

Table 1. *Classification of members of the Acoustical Society of America in 1932 and 2022*

Employer Type 1932		Employer Type 2022	
Colleges	16%	College/university	31%
Industrial laboratories (e.g., Bell Telephone, GE)	20%	Industry	12%
Acoustical material companies	23%	Consultant/self-employed	15%
Music and musical instruments	4%	Contractor	2%
Phonographs and talking picture field (RCA, Western Electric, Hollywood studios)	17%	Nonprofit	2%
Radio	6%	Government /government funded	7%
Miscellaneous	15%	Student	13%
		Retired	6%
		Other	1%
		None indicated	10%

on October 10, 1929. Fortunately, Celetex and other companies had given money for the journal just before the crash, which kept the Society out of debt. Two years later, in 1931, the ASA and four other societies began to purchase publishing services as a group that became the American Institute of Physics.

During and after World War II (WWII), vast amounts of new acoustical science topics were developing. At the end of WWII, Wallace Waterfall, who was already working for the US government on WWII assignments, was assigned by the National Defense Research Committee to publish results of that research and discoveries made in the field of sound during the war. Because of all the new information, the Journal went from quarterly and very thin to bimonthly and then to monthly to accommodate this growth.

For more information about the history of the ASA, look at the 25th anniversary program (see tinyurl.com/2p98xd4a), the 75th anniversary program (see tinyurl.com/2p9euktx), and the many oral histories collected by and about prominent ASA members (see asahistory.org/oral-histories).

Looking Toward the Future of the ASA

Times have changed. The majority of our scientific research presentations are funded federally or by other funding agencies. The practical aspects and commercial applications of acoustics are seen more in the exhibitions. But we are again moving toward a greater participation by commercial organizations (see **Table 1**). The uses and applications of acoustics are practical and many are commercial. We have several strategic plan task forces whose specific aim is to expand the Society's focus more toward practitioners and industry. I now discuss Task Force A and Task Force B and thank Adam Maxwell, chair of Task Force A, and Derek Knight, chair of Task Force B, for their input.

Task Force B: Better Engagement of Practitioners and Industry

Task Force B arose because of the 2019 Strategic Plan Retreat that concluded that practitioners and members from industry are a much higher proportion of the ASA membership than is reflected in the ASA leadership, both historically and today. Task Force B has been working to create programs and deliver experiences for industry and practitioner members that will increase participation, recognition, and leadership of members of these groups. The ASA members from these groups already give scientific presentations on acoustics. Greater involvement could include thematic special sessions reflecting the interests of industry, the increase in the membership of those in private practice and industry, the creation of mechanisms for recruitment of students to private companies, and the increase in corporate visibility through sponsorship.

One of Task Force B's endeavors, sponsored by Tony Hoover and former president Diane Kewley-Port, was to change the review process for electing ASA Fellows to include credentials beyond publications and grant credentials to better represent practitioners among ASA

Fellows. The modifications changed the lens through which candidates are evaluated to better represent the accomplishments of practitioners as well as those of academicians so that there would be a better balance of awardees.

The ASA Academy arose from a desire for professional training for practitioners who may be in other fields or need to broaden their acoustics focus. Michael Vorländer engaged colleagues to develop pilot courses in various technical areas that are currently in the planning phase. The intent is to offer a series of pilot courses in acoustics beginning in early 2023.

Task Force B has also been active in promoting sponsorships for the ASA. They cosponsored the first keynote lecture at the December 2020 Acoustics Virtually Everywhere meeting and suggested speakers from industry. Jim West and Ellington West were our first keynote speakers. Task Force B was also instrumental in providing potential sponsors and contacts in industry for the 2021 Seattle meeting.

Task Force A: Identification and Promotion of Emerging Scientific and Technical Areas

Professional societies always run the risk of losing their impact by remaining the same while their membership and the field change. One of the methods we use to prevent this is the Strategic Plan. Every three-to-four years, a retreat is held to create task forces to address noteworthy issues in the field or in the ASA. Task Forces A and B both emerged from this plan. Task Force A came about to ensure that the Society remains current as science and the field of acoustics grow and change. The goal of Task Force A is to identify emerging scientific and technical areas and create processes that will promote their inclusion in the ASA, to keep the Society relevant, and to promote cross-fertilization between technical areas.

Task Force A, among other things, has created and curated a list of about 15 emerging areas and ASA members who work in these areas as well as points of contact in other societies and journals that target these areas. The list is being used currently to identify speakers for the ASA Webinars. For 2022, about half of the Webinar speakers will be in emerging areas taken from this list. The list is also being used for suggestions for keynote speakers in current and future meetings. Another idea along this line has been to reinitiate the Distinguished Lecture program at the Society meetings with speakers in these areas. Finally, there are ideas to coordinate efforts with future special sessions of ASA meetings and special issues of *JASA* and to connect with relevant individuals in other societies and societies with which we might hold joint conferences.

My Last Column

This is my last column as president, and I want to take the time to say how enjoyable and rewarding this position has been. The other officers, managers, committees, and members are so committed to the future of the Society that it has been a pleasure to work with all of you.

At the close of the 25th Anniversary Celebration of the ASA in 1954, Hallowell Davis said,

> "The Acoustical Society of America is in a state of evolution. We don't know what the form of the Society will be or what the subject matter of the papers and the programs will be at the Hundredth Anniversary Celebration. We wish that we could look into the crystal ball. There is a crystal ball up here [pointing to the movie camera], but it is only half a crystal ball, it's a one-way affair, posterity is able to look at us, but we can't look back through that lens and see you on the other side. I wish we could. I know that we would find you as strange and quaint and amusing, in your ways, different from us as you find us as you look at our faces on the screen. However, you are our descendants, you carry on the torch" (from the Anectodal History of the Program, The Twenty-Fifth Anniversary Celebration of the Acoustical Society of America, The Forty-Seventh Meeting. *JASA* 26, 905 [1954]).

As the ASA approaches 100, it is so good to see that the Society and its membership carries on the torch referred to by Davis, and I too look forward to seeing where we go. I am honored to have been part of the process, and I want to encourage other members, and particularly our younger members who are the future of the ASA and of acoustics, in all its realms, to get engaged with the ASA, become part of leadership, and help shape the ASA and acoustics in the years up to the 100th Anniversary Celebration and well beyond.

I thank Elaine Moran, Director of Operations, for her invaluable contributions to this column.

Building Blood Vessels and Beyond Using Bubbles

Mitra Aliabouzar and Mario L. Fabiilli

Introduction

The axolotl (*Ambystoma mexicanum*), a type of salamander (see tinyurl.com/59u26vdm), has an incredible ability to regenerate entire limbs and other body parts that become damaged. Although humans are unable to match the axolotl, the capability of the human body to repair wounds is ultimately critical for our survival. Wound healing is a complex process driven by cells initially present at the wound site as well as cells that migrate into the wound environment. In general, cell behavior is guided by biochemical and biophysical "cues" in the local environment. Biochemical cues (e.g., proteins) are molecular in nature, whereas biophysical cues (e.g., stiffness) are mechanical and/or structural characteristics of the environment surrounding a cell. In the human body, the extracellular matrix is the environment surrounding each cell within solid tissue and contains large molecules like proteins and carbohydrates.

These biochemical and biophysical cues, which are regulated in both space and time by intricate pathways, cause a cell to undergo processes that directly or indirectly facilitate wound healing. Many wounds like minor cuts, scrapes, and bruises heal without a visit to a doctor's office. Other wounds may necessitate medical treatments like stitches or an orthopedic cast in addition to pharmaceuticals for the wound to properly heal. Surgical reconstruction and/or organ transplantation is needed when tissues or organs are severely damaged by trauma (e.g., car accident) or disease (e.g., cardiovascular, cancer). These higher risk and more invasive interventions are required when the damaged tissues or organs have a very limited ability to regain their structure and function via the body's normal wound-healing mechanisms. Unfortunately, there is a practical limit to the types of defects that can be surgically reconstructed. Moreover, some patients do not qualify for surgery because of other medical issues. Complicating matters further, the demand for organ transplantation exceeds the supply of donated organs and organ recipients often require long-term immunosuppressive drugs, both of which impact morbidity and quality of life.

Tissue Engineering and Regenerative Medicine

The field of tissue engineering and regenerative medicine (TERM) seeks to overcome limitations associated with conventional, medical interventions like surgery and organ transplantation. The goal of TERM is the development of biological constructs that facilitate restoration, maintenance, or regeneration of impaired or injured tissues/organs. A common strategy within TERM is the preprogrammed design of a construct consisting of a biocompatible scaffold loaded with cells and/or biochemical cues (**Figure 1A**). The scaffold provides a three-dimensional (3D) microenvironment for cells, thereby mimicking the function of the extracellular matrix.

The scaffold component of the construct often consists of a hydrogel, which is a porous, water-laden matrix consisting of natural (e.g., fibrin, collagen) or synthetic (e.g., dextran, polyethylene glycol) polymers. Hydrogels are made by cross-linking solutions of polymers to yield a solid-like material. Many commonly used hydrogels in TERM are biodegradable, which can assist with regenerative processes because they stay as long as needed and then disappear over time.

Constructs are implanted inside a living organism to assist with tissue regeneration. However, a problem with preprogramming the design of a construct is that it involves manipulating the physiochemical properties of the scaffold and its precursor components before the construct is implanted. This manipulation yields constructs with predefined patterns of biochemical and biophysical cues. For example, with hydrogels, the composition of the

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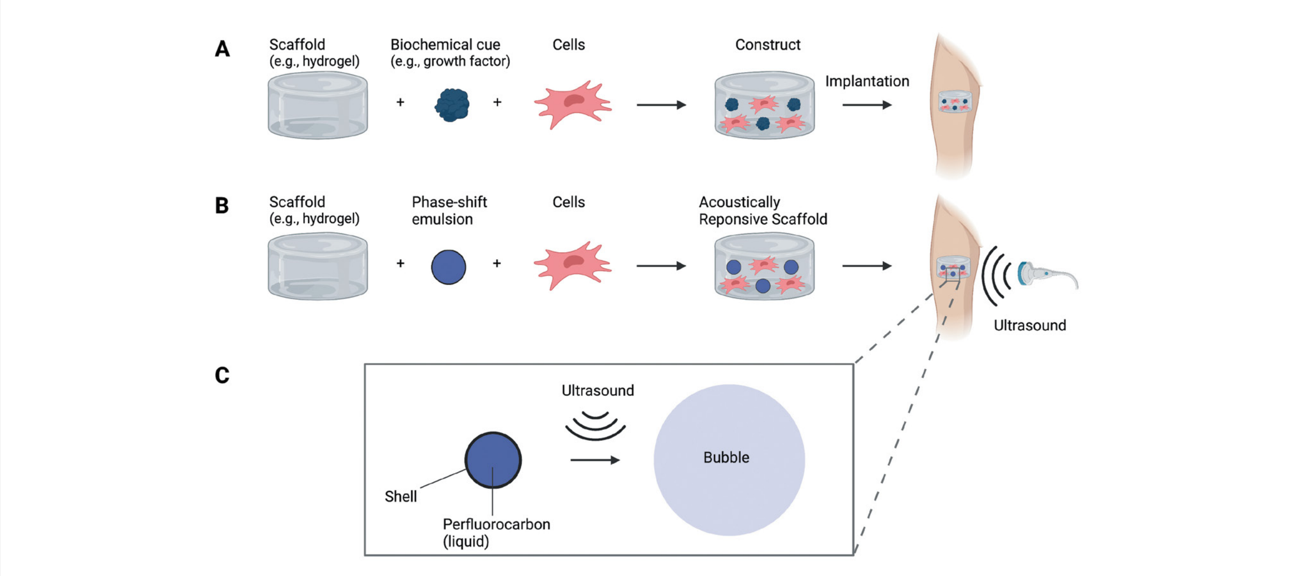


Figure 1. ***A:*** *constructs used in tissue engineering and regenerative medicine consist of a scaffold loaded with biochemical cues and/or cells. The construct is implanted within the body to facilitate regeneration at a particular location. A limitation of this common, preprogrammed paradigm is the inability to actively modulate biochemical and/or biophysical cues within the construct after implantation.* ***B:*** *an acoustically responsive scaffold (ARS) can be noninvasively controlled using ultrasound, thereby enabling spatiotemporal modulation of cues after implantation. The phase-shift emulsion within the ARS is responsive to ultrasound.* ***C:*** *acoustic droplet vaporization (ADV) is the process by which a phase-shift emulsion in the ARS is converted into gas bubbles using ultrasound. ADV enables modulation of biochemical and biophysical cues within the ARS.*

polymer network and cross-linking conditions impact the rate at which biochemical cues are released from the hydrogel as well as its stiffness. But the preprogrammed design may not be best for the specific site of implantation. Or the design could be well suited at the time of implantation, but then its suitability decreases over time.

After implantation, the ability to dynamically modulate cues within a preprogrammed construct, and hence tissue regeneration, in an on-demand manner defined by a physician or even a patient is extremely limited. From a basic science perspective, the reliance on a preprogrammed design has hampered elucidating the roles of fundamental, biochemical, and biophysical cues in situ. In fact, this points to the need for a better understanding of these cues to help drive the development of new, regenerative therapies. Indeed, from an applied perspective, the preprogrammed design hinders real-time personalization of regenerative therapy for the simple reason that there is no way to easily adjust the performance of a preprogrammed construct in situ. These shortcomings have led to the development of constructs in which biochemical and/or biophysical cues can be externally controlled using light, heat, electricity, and magnetic fields. However, these stimuli are limited by factors such as a superficial depth of penetration, the need for invasive procedures, and/or poor spatial localization.

The Sound of Healing: Ultrasound and Regeneration

Ultrasound has been exploited in many regenerative applications because it can noninvasively produce desired thermal and mechanical bioeffects in a spatiotemporally regulated manner. These bioeffects can be produced at depths of up to 10 centimeters within the human body. Low-intensity ultrasound (LIUS) is one of the most studied ultrasound techniques and can be used to induce a myriad of biological responses including blood vessel growth and bone repair. The exact mechanisms underpinning the actions of LIUS in regeneration are being actively investigated. Studies highlight the involvement of mechanotransduction, whereby mechanical forces generated by LIUS activate mechanically sensitive receptors in cells, which leads to biochemical signaling (Sato et al., 2014).

Pulsed, focused ultrasound with a higher intensity than LIUS has been shown to transiently increase levels of signaling proteins within tissue. This, in turn, can locally attract cells that are intravenously injected, which can help revascularize ischemic tissue (Tebebi et al., 2017). Acoustic shock waves, which in addition to LIUS have clinically approved uses, promote healing of bone and soft tissues (Simplicio et al., 2020). Ultrasound can also pattern cells within hydrogels, which assist with the growth of blood vessel-like structures (Garvin et al., 2011). Therefore, as seen with these examples, ultrasound can help drive regeneration in many ways.

The (Sort of) New Kid on the Block

A new, ultrasound-based approach for controlling biochemical and biophysical cues in tissue regeneration involves phase-shift emulsions: shell-stabilized liquid droplets that can be converted into gas bubbles in situ using ultrasound. Phase-shift emulsions use perfluorocarbon (PFC) liquids because they have favorable thermodynamic properties as well as a high biocompatibility. They also have vapor pressures that are an order of magnitude higher than that of water. The volatility of a PFC liquid provides a thermodynamic driving force for the liquid to phase transition into a gas.

The liquid-to-gas transition requires a certain amount of thermal energy or tensile stress (i.e., negative pressure). Ultrasound can trigger a phase transition in a PFC liquid without the generation of heat. Specifically, the negative component of the ultrasound wave reduces the local pressure below the vapor pressure of the PFC liquid, thereby making vaporization thermodynamically favorable.

A liquid can exist in a metastable state (i.e., below its saturated vapor pressure) while experiencing a negative pressure. Ultimately, as the magnitude of the negative pressure increases, vapor bubbles spontaneously form within the liquid. These bubbles grow until their internal pressure reaches the equilibrium pressure of the liquid (Fisher, 1948). The same concept is employed in phase-shift emulsions where the application of ultrasound induces bubble formation in a process known as acoustic droplet vaporization (ADV).

Acoustic Droplet Vaporization

The concept of ADV can be traced back to the 1950s and the late Donald Glaser, who was awarded the Nobel Prize in Physics for developing bubble chambers. These chambers contained a superheated liquid and enabled detection of atomic particles that left a path of bubbles as they traversed the liquid. Building on this work, in 1979, the late Robert Apfel (see bit.ly/AT-Apfel), former president of the Acoustical Society of America and recipient of the Society's Gold Medal, developed a radiation dosimeter in which the superheated liquid was fractionated into droplets. Apfel (1998) patented this technology, envisioning that ultrasound, in addition to radiation, could vaporize the droplets (i.e., phase-shift emulsion), which could be used in biomedical applications. The first experimental results on ADV were published by Kripfgans et al. (2000). Currently, many groups around the world are actively investigating phase-shift emulsions, ADV, and their biomedical applications, as seen in earlier articles in *Acoustics Today* (Burgess and Porter, 2015; Gray et al., 2019).

ADV is a threshold phenomenon, with the minimum acoustic pressure required to generate ADV termed the ADV threshold. The ADV threshold depends significantly on the physical properties of the phase-shift emulsion (e.g., diameter, molecular weight of the PFC species) as well as acoustic parameters (e.g., frequency) (Schad and Hynynen, 2010). For ultrasound frequencies of 1-10 MHz, ADV thresholds are in the megapascal range (i.e., peak negative pressure).

Phase-shift emulsions possess some distinct advantages compared with the microbubbles that are used diagnostically as ultrasound contrast agents to visualize blood flow and therapeutically to enhance drug delivery. One such advantage is that emulsions exhibit greater stability than microbubbles because of their liquid cores. Compared with microbubbles that only persist for minutes after injection into the body, emulsions can persist for much longer (e.g., hours to days). Another advantage is that emulsions have a greater drug-loading capacity. Drugs can be loaded into the liquid core of the emulsion compared with microbubbles where drugs are loaded into the shell.

Phase-shift emulsions for tissue regeneration are not directly injected into the bloodstream, which is typically how the emulsions are used in many other biomedical applications. Rather, the emulsions are incorporated into hydrogels to yield an acoustically responsive scaffold (ARS) that can be implanted into the body (**Figure 1**, **B** and **C**). This administration method also enables the use of larger diameter emulsions (e.g., >6 μm), which can be formulated more easily in uniform sizes compared

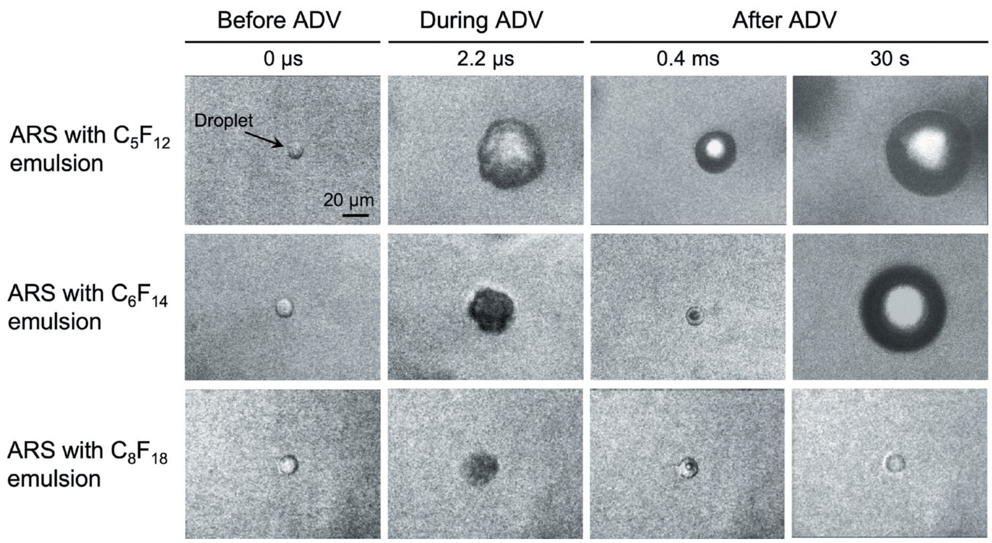


Figure 2. *In an ARS, bubble dynamics during and after ADV were dependent on the perfluorocarbon (PFC) liquid in the phase-shift emulsion. Longitudinal images, which were taken using ultra-high-speed microscopy, are shown for ARSs with emulsions containing perfluoropentane (C_5F_{12}; **top**), perfluorohexane (C_6F_{14}; **center**), or perfluorooctane (C_8F_{18}; **bottom**). In each series of images, a single droplet is shown during three stages: before (**left**), during (**center**), and after (**right**) ADV. During ADV, ultrasound caused formation of vapor in the PFC phase. Note the differences in bubble dynamics once the ultrasound is turned off (i.e., after ADV). A stable bubble was formed with C_5F_{12} and C_6F_{14}. With C_8F_{18}, the generated bubble recondensed.*

with smaller emulsions. Additionally, unlike other applications that often utilize lower molecular weight (and hence higher volatility) PFCs like perfluorobutane (i.e., C_4F_{10}) (Sheeran et al., 2016) or perfluoropentane (i.e., C_5F_{12}) (Mercado-Shekhar et al., 2019), emulsions in ARSs are typically formulated with higher boiling point PFCs like perfluorohexane (i.e., C_6F_{14}) or perfluorooctane (i.e., C_8F_{18}). These higher molecular weight PFCs offer better thermal stability by eliminating the potential for spontaneous bubble formation. Higher molecular weight PFCs also yield interesting bubble dynamics during and after ADV that can be utilized for specific applications. For example, emulsions with lower molecular weight PFCs undergo irreversible vaporization, where a stable bubble is formed (**Figure 2**); this yields a complete release of a drug loaded within the emulsion. Comparatively, with higher molecular weight PFCs, the generated bubble recondenses; this yields partial release of a drug.

Building Blood Vessels Using Bubbles

Conventional treatments for ischemic cardiovascular disease, which is characterized by insufficient blood flow, include bypass surgery and endovascular procedures. With the former, a healthy blood vessel is harvested from the patient's body and surgically connected to circumvent a blocked blood vessel. With the latter, a catheter is used to remove the occluding material (e.g., atherosclerotic plaque) in the blocked vessel, and removal is sometimes followed by the installation of a stent in the vessel. However, current treatments for cardiovascular disease are insufficient. For example, with critical limb ischemia, an advanced stage of peripheral artery disease characterized by poor blood flow in the leg, 25% of patients are ineligible for current treatments because of other medical issues and 29% of patients will either die or undergo a major amputation within one year of diagnosis.

Due to issues associated with standard interventions, alternative treatments are constantly being sought. One approach being investigated is the use of proteins to stimulate blood vessel growth. However, despite success in animal models, clinical translation has remained a challenge for multiple reasons. One critical limitation is that simply injecting the proteins into the body, in either the bloodstream or muscle, is ineffective and can cause serious side effects. Incorporating

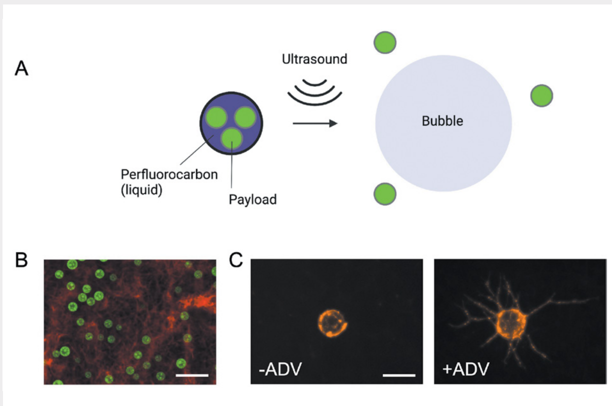


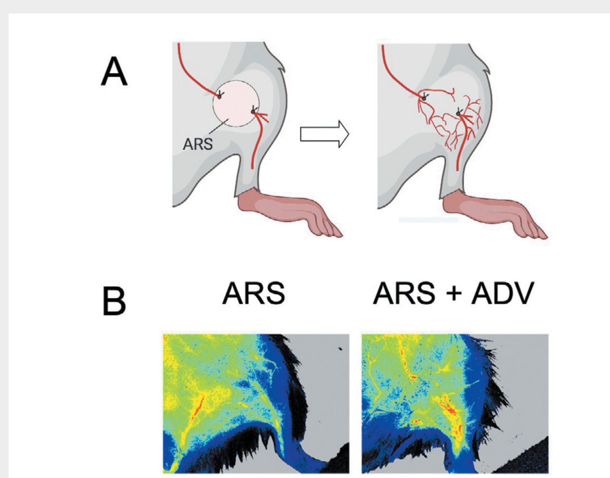
Figure 3. ***A:*** *payloads are encapsulated within a phase-shift emulsion using a double-emulsion approach. The payload is contained within tiny water droplets that are surrounded by liquid PFC. The encapsulated payload is released during ADV when the generated bubble disrupts the morphology of the double emulsion.* ***B:*** *the microstructure of an ARS was visualized using fluorescence microscopy, with the fibrin hydrogel matrix (**red**) and phase-shift emulsion (**green**) shown. Scale bar, 10 µm.* ***C:*** *ADV was used to release basic fibroblast growth factor, which controlled the growth of an in vitro model of blood vessels. The model consisted of microbeads coated with endothelial cells (**orange**), and fibroblasts. In this model, endothelial cells form tubes that are similar to blood vessels in the presence of appropriate biochemical cues. Note the presence of tubules emanating from the microbead for the +ADV condition (**right**), whereas no tubules were seen in the −ADV condition (**left**). Scale bar, 200 µm.*

the protein into a hydrogel is a more biocompatible approach, as discussed in **Tissue Engineering and Regenerative Medicine**, but there is a relatively limited control afforded by this method. Furthermore, the optimal delivery parameters for these potent proteins are still being determined (Briquez et al., 2016).

To attempt to solve some of these issues, ADV has been used to spatiotemporally control the release of proteins from ARSs using the following approach. A therapeutic payload like basic fibroblast growth factor (bFGF), a protein that stimulates blood vessel growth, is encapsulated in a phase-shift emulsion using a double-emulsion technique (**Figure 3A**). In this technique, bFGF is contained within tiny water droplets surrounded by a liquid PFC. Due to its hydrophobicity, the liquid PFC inhibits the release of bFGF from the emulsion. Ultrasound is then applied to the ARS to generate ADV and this results in the release of bFGF because the emulsion morphology is disrupted by bubble formation. Controlled stimulation of blood vessel growth has been demonstrated in both in vitro (**Figure 3B**) and in vivo studies with ARSs (Moncion et al., 2017; Dong et al., 2019). Human studies have not yet been conducted.

In a recent study utilizing a mouse model of critical limb ischemia (Jin et al., 2021), mice that received ARSs with bFGF in conjunction with periodic applications of ADV displayed significantly better therapeutic outcomes (e.g., increased blood vessel growth, increased perfusion, decreased tissue necrosis, decreased fibrosis) compared with all other experimental groups (**Figure 4**). In another study, focused ultrasound was used to spatially pattern ADV and, hence, the release of bFGF within ARSs. This led to spatially defined patterns of blood vessel formation and host cell migration (Huang et al., 2021). Overall,

Figure 4. *Blood vessel growth and perfusion were stimulated when ADV released basic fibroblast growth factor from an ARS.* ***A:*** *an ARS was implanted in a mouse model of peripheral artery disease. The model involved surgically removing a segment of artery in the leg, thereby causing a dramatic decrease in perfusion. Subsequently, an ARS was placed at the site of vessel removal.* ***B:*** *using a laser-based technique, perfusion in the leg was measured and is displayed as a colormap. Greater perfusion, as seen with the presence of the warmer colors (e.g., **yellow**, **orange**, and **red**), was observed for the ARS+ADV group compared with the group receiving only an ARS, as seen with the presence of the cooler colors (e.g., **blue** and **green**). Reprinted from Jin et al. (2021), with permission from Elsevier.*



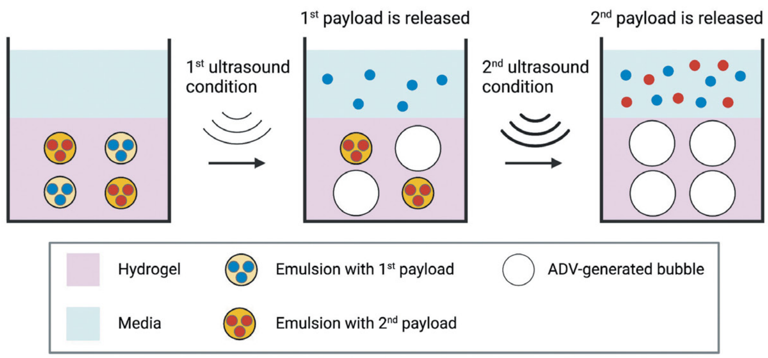


Figure 5. *Two payloads can be sequentially released from an ARS. Each payload is encapsulated within a separate phase-shift emulsion. The first payload is encapsulated in an emulsion with a lower ADV threshold than the second payload. Sequential ultrasound applications of lower and higher amplitudes release the first and second payloads, respectively. Adapted from Moncion et al. (2018), with permission from Elsevier.*

these studies highlight the exciting potential of using ADV and ARSs for stimulating blood vessel growth and in developing new treatments for cardiovascular disease.

Two Can Be Better Than One: Sequential Release Using Ultrasound

Complex, regenerative processes like blood vessel or bone growth require multiple signaling proteins. In addition to their spatial presentation, the temporal sequence of these proteins is critical. For example, bFGF and platelet-derived growth factor BB (PDGF-BB) are both involved in the growth of new blood vessels. bFGF stimulates the initial growth of the blood vessel, particularly the sprouting of endothelial cells that form the inner lining (i.e., lumen) of the vessel. PDGF-BB stimulates other cells to stabilize the outer lining of the vessel, thereby rendering a mature vessel. However, if bFGF and PDGF-BB are present simultaneously, the proteins will inhibit each other, thereby disrupting blood vessel formation (Tengood et al., 2011).

By exploiting the properties of the ADV threshold, ARSs can be designed to enable sequential release of two therapeutic payloads. This involves encapsulating each payload within separate emulsions. The ARS is then exposed to ultrasound at acoustic conditions that will selectively release the first payload without causing release of the second payload. At a later time point, the ARS is exposed to acoustic conditions that release the second payload. This concept has been demonstrated using two strategies: (1) ADV at a single ultrasound frequency (e.g., 2.5 MHz) using two peak rarefactional pressures (e.g., 2 MPa followed by 8 MPa) (**Figure 5**) (Moncion et al., 2018) and (2) ADV at two different ultrasound frequencies (e.g., 8.6 MHz followed by 2.5 MHz) (Aliabouzar et al., 2021). An ultrasound standing wave field has also been used for the sequential release from bilayer ARSs, in which each layer contains a different payload-carrying emulsion (Aliabouzar et al., 2020a).

Use the Force: Control of Biophysical Cues

A cell can sense biophysical cues via receptors linking structural proteins within the cell to the microenvironment surrounding the cell. Cell behavior is significantly impacted by these biophysical cues. For example, mesenchymal stromal cells (MSCs) are cells that can change into more specialized types of cells. When grown on hydrogels, MSCs change into different types of specialized cells based on the stiffness of the hydrogels (Engler et al., 2006). Beyond stiffness, other parameters that impact cellular processes include elasticity, porosity, fiber density, surface roughness, and surface curvature.

ADV enables the spatiotemporal modulation of biophysical properties in ARSs. During ADV, the liquid PFC phase within the phase-shift emulsion undergoes a dramatic increase in volume (up to 125-fold) as it is converted into a gas. Stable bubbles grow further in size due to inward diffusion of dissolved gases from the surrounding environment. In an ARS, stable bubbles remain trapped in the hydrogel matrix, thereby locally impacting both the

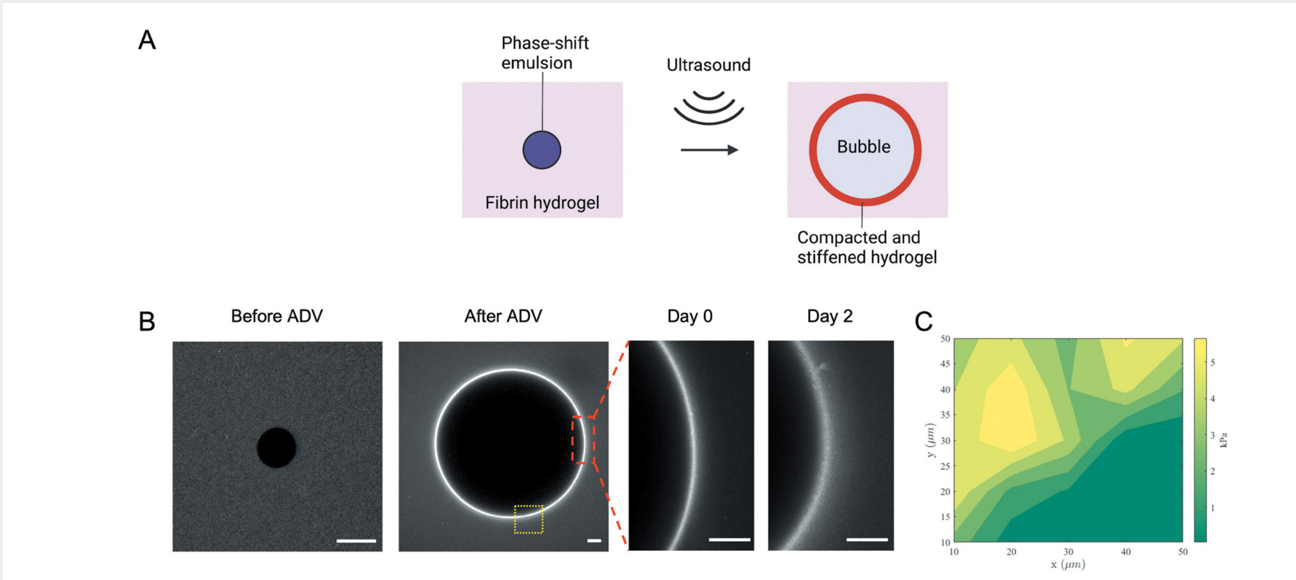


Figure 6. ***A:*** *in a strain-stiffening material like fibrin, ADV locally compacts and stiffens the fibrin matrix surrounding the bubble.* ***B:*** *the fluorescently labeled fibrin matrix was visualized with confocal microscopy. After ADV, the bubble compacted the matrix, causing an increase in fluorescence intensity that persisted over the course of days. Scale bar, 20 μm. Reprinted from Humphries et al. (2022), with permission from Wiley.* ***C:*** *Young's modulus was mapped adjacent to the bubble in a location denoted by* ***yellow box*** *in* ***B****. Note the higher moduli proximal to the bubble (****yellow****) versus the lower moduli distal to the bubble (****green****). Reprinted from Farrell et al. (2022), with permission from Elsevier.*

structural and mechanical properties of the hydrogel (Fabiilli et al., 2013; Aliabouzar et al., 2020b). In ARSs made with fibrin, bubbles radially compacted the fibrin matrix surrounding them while simultaneously increasing its stiffness and decreasing its porosity (**Figure 6**). Fibrin is a protein found in blood clots and is an incredibly biocompatible hydrogel for cells. As bubbles grew in size, there was additional compaction and stiffening of the matrix. In fibrin, matrix compaction leads to an increase in matrix stiffness, a behavior known as strain stiffening.

ADV-induced stiffening can have broad biomedical applications. A recent study investigated the ability to change fibroblasts into myofibroblasts in ARSs (Farrell et al., 2022). Fibroblasts are a common cell type found in connective tissue that can change into myofibroblasts when in a stiffened environment. Cells in stiffened regions of fibrin adjacent to bubbles exhibited more characteristics of myofibroblasts compared with cells in less stiffened regions further away from bubbles. Myofibroblasts play a key role in the repair of connective tissues. Thus, ADV could assist with understanding fibrosis, a disease characterized by the sustained presence of myofibroblasts, as well as developing therapies for chronic wounds that contain insufficient numbers of myofibroblasts. In another study, cellular signaling in a cancer model was modulated in ARSs using ADV (Humphries et al., 2022). Therefore, ADV could help elucidate how biophysical changes to the extracellular matrix impact tumor biology, which could lead to novel treatment approaches.

In contrast to bubbles that grow over time, ADV can also generate liquid-filled pores within ARSs. These pores are generated based on the collapse of the ADV-generated bubble, which causes localized erosion of the hydrogel matrix in the ARS. It has been shown that generation of pores within an ARS, in combination with bFGF release, increased migration of host cells into the implant (Lu et al., 2020). These host cells were cells that were initially surrounding the ARS on implantation. Comparatively, stable bubbles hindered host cell migration into an ARS. Thus, ADV can modulate cell migration, which can assist in directing regenerative processes.

The Next Generation: Three-Dimensional Bioprinting of Acoustically Responsive Scaffolds

The shape of an ARS is dictated by the shape of the container that holds the polymer solution as it is cross-linked into a solid material. Thus, there is a practical limit to what geometries can be achieved, and there is a limited ability to generate complex patterns of emulsions and hydrogel matrices. ARSs with patient-specific geometry (e.g., to fit in a wound area) as well as precise, spatial patterning of the hydrogel matrix and multiple phase-shift emulsions can further advance their applications in TERM. However, developing reproducible ARSs with the above-mentioned features requires advanced fabrication methods beyond conventional bulk polymerization techniques. To do this, 3D bioprinting is used in the development of such ARSs through precise layer-by-layer deposition of the hydrogel component of the ARS or phase-shift emulsions within the ARS based on user-defined computer-aided design.

Using an extrusion-based bioprinting technique, ARSs with spatially patterned phase-shift emulsions were fabricated (**Figure 7**) (Aliabouzar et al., 2022). ADV can be generated at significantly higher spatial resolutions in bioprinted ARSs compared with conventional ARSs. This implies that the ADV-induced modulation of biochemical and biophysical cues could be spatially patterned at higher resolutions with 3D bioprinting. Additionally, bioprinting enabled micropatterning of both phase-shift emulsions and cells in distinct patterns in ARSs.

Bioprinting offers another advantage of fabricating ARSs with different mechanical properties within each layer, which can provide a platform to tune the response of ADV-generated bubbles and, in turn, the associated biophysical and biochemical effects. Overall, integrating ADV with 3D bioprinting, which is incredibly underdeveloped, can open new opportunities in regenerative medicine.

Final Thoughts

Phase-shift emulsions, ARSs, and ADV are tools that can help unravel the complexities of tissue regeneration as well as drive the development of new, regenerative therapies via the modulation of biochemical and biophysical cues. The ability to noninvasively modulate an ARS using ADV in an on-demand, spatiotemporally controlled manner is a dramatic paradigm shift compared with conventional hydrogels widely used within TERM. A better understanding of acoustically driven interactions in the ARS, particularly with cells, will help spur their translational advancement, both within TERM and in other applications.

Acknowledgments

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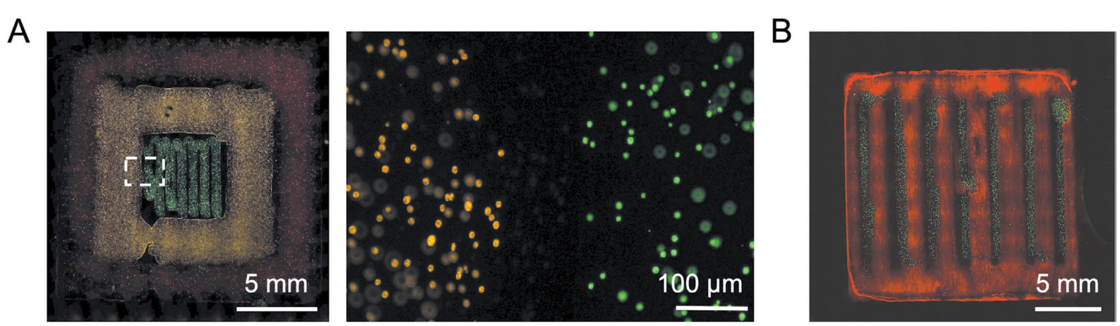
Figure 7. *Three-dimensional (3D) bioprinting generated ARSs with complex structures.* ***A:*** *three phase-shift emulsions with different fluorescent payloads (i.e.,* ***red***, ***yellow***, *and* ***green dextran****) were printed in a hydrogel matrix consisting of alginate and hyaluronic acid (****left****).* ***Right:*** *zoomed-in region of* ***white box*** *on* ***left****.* ***B:*** *reservoirs of emulsion (****green****) were printed in a matrix of fibrin and hyaluronic acid (****red****). Reprinted from Aliabouzar et al. (2022), with permission from Elsevier.*



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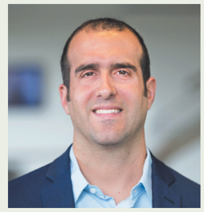

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Teaching Architectural Acoustics to Students of Various Disciplines

Daniel Butko

Introduction

The words *architectural* and *acoustics* perhaps conjure thoughts of buildings or spaces with specific acoustic requirements (such as music halls, recording studios, auditoriums, and libraries) and/or the design professionals who have spent their careers focused on the topic. However, this is just the beginning, and this article explains the methods of introducing students of various backgrounds and areas of study to the aural aspects of various occupancies and forms of architecture through discussions, lessons, assignments, field trips, and projects. Have you ever noticed that the word *aural* is literally in *a*rchitect*ural*? The actual beginning and end of the word spell out the entire point of this article: the integration of the aural in architecture and the built environment. I ask students, "Are all aural?" Say it slowly, and the play on words begins a discussion of building types that require acoustical attention. The compound answer becomes evident: all aspects of the built environment have an aural component.

Sound waves are all around us; they come in many shapes (frequency) and sizes (amplitude) and are felt as much as heard by the human body through vibrations in even those without the ability to hear. Although the qualities of sound waves vary, there are sources of sound, paths in which the sound waves travel, and receivers who then receive, process, and/or record the information. Most people tend to anecdotally quantify sound, and its often-undesirable counterpart noise, based on feelings or preferences. That's one way to begin; listen and be receptive of how vibrations through air and materials make you feel. Observations, coupled with quantifiable data, influence designers toward supportive acoustic design concepts. Architecture is more than meets the eye, especially when it meets the ear.

This article outlines the introduction and application of acoustical vocabulary, lessons, and criteria through the following educational opportunities: (1) assigned required courses; (2) elective and independent-study courses; and (3) research, practice, and service-learning projects.

Why Architecture?

To discuss architectural acoustics, there should be some relationship between what an architect does and how someone begins a career in architecture. We all likely know that architects design buildings. The scope of responsibilities of the word *design* relating to the health, safety, and welfare of the building occupants is usually not as glamorous as the aesthetics or landmark status associated with some projects. With requirements for training and licensure in place around the world, the days of being a self-professed architect/master builder are gone. Aside from numerous states now offering alternate/alternative paths to licensure that do not always include a formal postsecondary education, a high percentage of eventually licensed architects opt for at least a Bachelor of Architecture degree that typically spans 5 years (10 semesters), followed by an internship in a firm and a multiphase Architectural Registration Exam (ARE). On the other hand, at the time this article was written, it is believed only the state of Oregon offers a license for acoustical engineers, so the path toward acoustician/acoustical consultant is less regulatory, but the knowledge and experience are still vital in the shaping of acoustically successful architecture. It is the intersection of these career paths that sets the stage of how to teach acoustics housed within an accredited architecture program to various disciplines and emphasizes the importance of the art and science in the profession.

Prospective architecture students may be influenced through various forms of media, rendering architecture through visual means and text, and often find the formal training different from preconceived expectations. An understanding of and appreciation for architecture is often the result of experiencing it through occupant senses, including the aural environment created when materials are erected and a form is created. Those of us fortunate

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enough to be in teaching/instruction roles have opportunities to not only share our knowledge but to also build new experiences with students as we explore the many facets of architecture. As the Dunning-Kruger effect reveals, we don't know what we don't know and we aren't aware that we don't know it (Dunning, 2011). Keeping an attitude of a lifelong learner helps break our limited awareness and align perception with reality. Although there are various influences that lead students to study architecture, I have not met a student who answers the "What led you to enroll in architecture courses" question with anything to do with acoustics or the aural environment. Perhaps more acousticians need to attend high-school career days! Nonetheless, I am pleased to introduce students to the invisible realm of acoustics pertaining to health, safety, and welfare in the built environment.

I brought my love and knowledge of acoustics to the University of Oklahoma (OU; Norman) Gibbs College of Architecture (GCA) through an introduction to design concepts and sensibilities, technical and material science, and passive and active systems. The GCA houses various majors and offers courses to students from colleges across campus, so my sphere of influence is not limited to architecture students. To date, I have introduced over 1,500 undergraduate and graduate students of diverse backgrounds and disciplines to architecture and associated aural environments. The GCA does not have a dedicated acoustics laboratory (yet) or series of courses specializing in this area of study, so the scaffolding of topics is completed through hands-on experiments, field measurements and data collection, the study of musical instruments, precedent studies and literature reviews, laboratory and manufacturing facility tours, and material prototype fabrication with industry partners. Combining experience and an interest in architecture and acoustics as a common thread of pedagogy throughout various teaching opportunities helps students analyze and design spaces that are acoustically supportive for their functions.

Pedagogy: Method and Practice of Teaching

Students learn the results of shaping space not from merely the cool factor of twisting planes in software or molding physical materials into an attractive form but from how the shape of space and the materials used to delineate an enclosure have embodied results that impact the health, safety, and welfare of occupants. The enclosing elements, which define exterior from interior space, often have codependent/symbiotic thermal, structural, air quality (from outgassing), fire and smoke resistance, and acoustical properties that can be measured and accounted for during design. Obviously, there are various other factors such as how color, texture, patterns, and the composition of materials impact/affect the mood and atmosphere. Learning how design decisions result in compound relationships with occupants helps students base architectural decisions on more than mere aesthetics. Beauty can be the functional result of all the influences.

What is a pedagogical approach or, more specifically, my approach to teaching architecture with a relationship to acoustical properties? My passion is for people to understand architecture in a way that encourages, edifies, educates, entertains, and evokes responses from occupants. There are various approaches to teaching that are expressions of personalities, experiences, and attempts to convey content coupled with audience reception. Architecture programs are evaluated through an accreditation process requiring assignment goals and learning objectives to be defined as demonstrated through understanding and ability. Lecture and design studio courses provide opportunities for students to convey knowledge through exams, assignments, and design proposals that embody the course content. Assessment of acoustic impact on successful design can be aligned with meeting required program and student criteria.

Vitruvius, a first-century Roman architect, engineer, and author, characterized sound propagation through air and materials like a wave from a pebble cast into a calm pool of water. Those ripples of resonating content are a metaphor for the learning process: repetition, reinforcement, and demonstration of both understanding and ability. Today, I wonder if people do not really listen to their surroundings; they may hear, but do they really listen? All too often the architects of tomorrow are wearing earbuds today. The first step is to encourage students to listen to spaces. Architecture is the physical medium changing a free field into a series of materials that reflect, diffuse, and absorb frequencies. By placing students in that context, they experience how sound waves and vibrations relate to everything in the built environment. I teach students to evaluate the shape of occupied and unoccupied volumes of space, the materials used to define enclosure, and associated quantifiable acoustical data such as sound transmission class (STC);

impact insulation class (IIC); reverberation time (RT); noise criteria (NC); noise reduction coefficient (NRC); and impulse response (IR), clarity (C_{50} and C_{80}), and speech transmission index (STI). It is also important to point students to physical scale models and software as tools for learning and developing spatial relationships.

Students are also introduced to codes, regulations, and guidelines that contribute to aural environments. Building codes and various organizations including Leadership in Energy and Environmental Design, Living Building Challenge, the American Institute of Architects (AIA) Framework/Committee on the Environment (COTE), the International Well Building Institute, the Whole Building Design Guide, and *The 9 Foundations of a Healthy Building* (see 9foundations.com) uphold occupant health, safety, and welfare and advocate for acoustics. The report *14 Patterns of Biophilic Design* (see terrapinbrightgreen.com/reports/14-patterns) showcases several aspects of physiological and psychological restoration through access to nature sounds. Students quickly realize the practically countless aspects of architecture and acoustics are a result of (1) "static" materials and form of the space and (2) "dynamic" interactions (interior and exterior): how people, materials, systems, and weather interact.

It would not be fair to merely focus on airborne sound as the star of the acoustics world. Architecture is a vehicle for all abilities and lies somewhere between form and function. In 1896, architect Louis Sullivan coined "form follows function." The function of the built environment offers an experiential aural environment seldom discussed or presented in the general realm of architecture. It leaves some of us questioning how the function of the space can be supported/successful without attention to how the space sounds. We should not always gravitate toward people with hearing abilities as the only occupants; we need to also account for humans with limited or no ability to hear, animals, technology, and artificial intelligence. During an interview in 1959, architect Ludwig Mies van der Rohe said, "Architecture starts when you carefully put two bricks together," but acousticians are likely asking, for example, "Are the bricks shifted out of plane to create diffusion, what is the cubic volume and RT of the resultant space, and what are the STC and NRC values." Let us also then realize specific acoustical criteria results from the form of the space defined by the surrounding materials.

Another branch of teaching includes inviting guest lecturers from various disciplines, participating in project reviews, reading invited and accepted conference and paper presentations, leading Continuing Education/Learning Unit sessions for various organizations and design professionals, and presenting at school career days that allow for the chance to introduce and inform diverse audiences other than clients and students about the far-reaching aspects of architectural acoustics.

Required Courses: Blending into Everyday Curriculum

The required semester-based Architectural Design Studios, Systems, and Materials and Methods courses in the BArch and MArch programs for which I am assigned include students from other disciplines. Regardless of the course description, most goals and objectives in my courses also include a relationship with architectural acoustics. If the assignment is about rhythm, patterns, or composition, I tie it back to music. If discussions are about point, line, plane, and spatial relationships (aka beginning design standard lessons), I offer comments about how decisions made

Figure 1. ***Top:*** *example of a design studio where students craft additive and subtractive models using materials such as wood, acrylic, foam, and Hydro-Stone.* ***Bottom:*** *wall-mounted and ceiling-hung models from an assignment focused on developing articulated panels that provide lighting and acoustic interactions.*

with those design elements could result in flutter echo or reverberation in occupied spaces depending on materiality, layered arrangements, and cubic volume. Students begin to understand the connections among surface articulation, proportions, and density relating to acoustical reflection, diffusion, and absorption. I also try to find common ground, like relating architecture to the bass and treble controls on their car radio (or a 31-band equalizer for the audiophile), to the hue and contrast adjustments on photographs, or to how architecture might alter wave-based forms of sound and light depending on material qualities and spatial form (**Figure 1**). Architecture becomes the interactive element that can support or deter from true reference, both aesthetically and aurally.

Although I have coordinated and instructed several BArch and MArch program courses, the integrated/comprehensive capstone studio has been a constant throughout the years. Students are required to integrate mechanical, electrical, plumbing, acoustical, fire resistance, thermal properties, site conditions, community engagement, and overall sustainable and resilient design concepts into individual projects. The process includes research of precedent studies, code analysis, data collection, project development through detailed drawings, and feedback from practicing design professionals. Systems courses integrated into design studios allow a deeper understanding of mechanical, electrical, and plumbing (MEP) systems including associated noise. It's one thing to tell students heating, ventilation, and air conditioning systems produce noise, but it helps the learning process to go the extra step and show them through real-time analysis (RTA) graphs the span of frequencies associated with the air handling unit, ductwork, and vents/diffusers, for example. Those measured and understood values then contribute to air handling unit locations, ductwork shapes, distribution distances, and wall and floor assembly layers to achieve desired NC ratings.

I tell students hard parallel walls that are not articulated will likely provide a flutter echo. It also helps to tell them what might appear to be wasted space by splaying or creating odd-shaped cavities between adjacent spaces provide opportunities for mechanical systems or storage areas. It's surprising to most students when I suggest designing spaces without equal or multiples of dimensions to avoid resonant frequencies and then proceed to sound out the woo woo sounds associated with standing waves. We have become sound machines when describing typical acoustical deficiencies. Students go around whooping, clapping, and shouting "reverberation is the persistence of sound" in most spaces they enter, immediately activating the space and yielding responses.

We take a lot of field trips. I have taken students to acoustics labs, consultant offices, music stores, parks, art districts, recording studios, and music halls. I direct attention to MEP system locations and how they relate to or are concealed in floors, walls, or ceilings (**Figure 2**). We discuss sound-isolation techniques, system integration, power-conditioning requirements, and how spaces are shaped to promote accurate audio referencing.

Some design projects challenge students to jump scales and translate function and interaction beyond the typical scaled

Figure 2. *On a field trip, students' attention was drawn upward to the vertical sound baffles concealing mechanical systems (**left**) and a colorful absorbent wall finish flanking a large open staircase (**right**). Students asked questions and connected discussions in class with inhabitable space.*

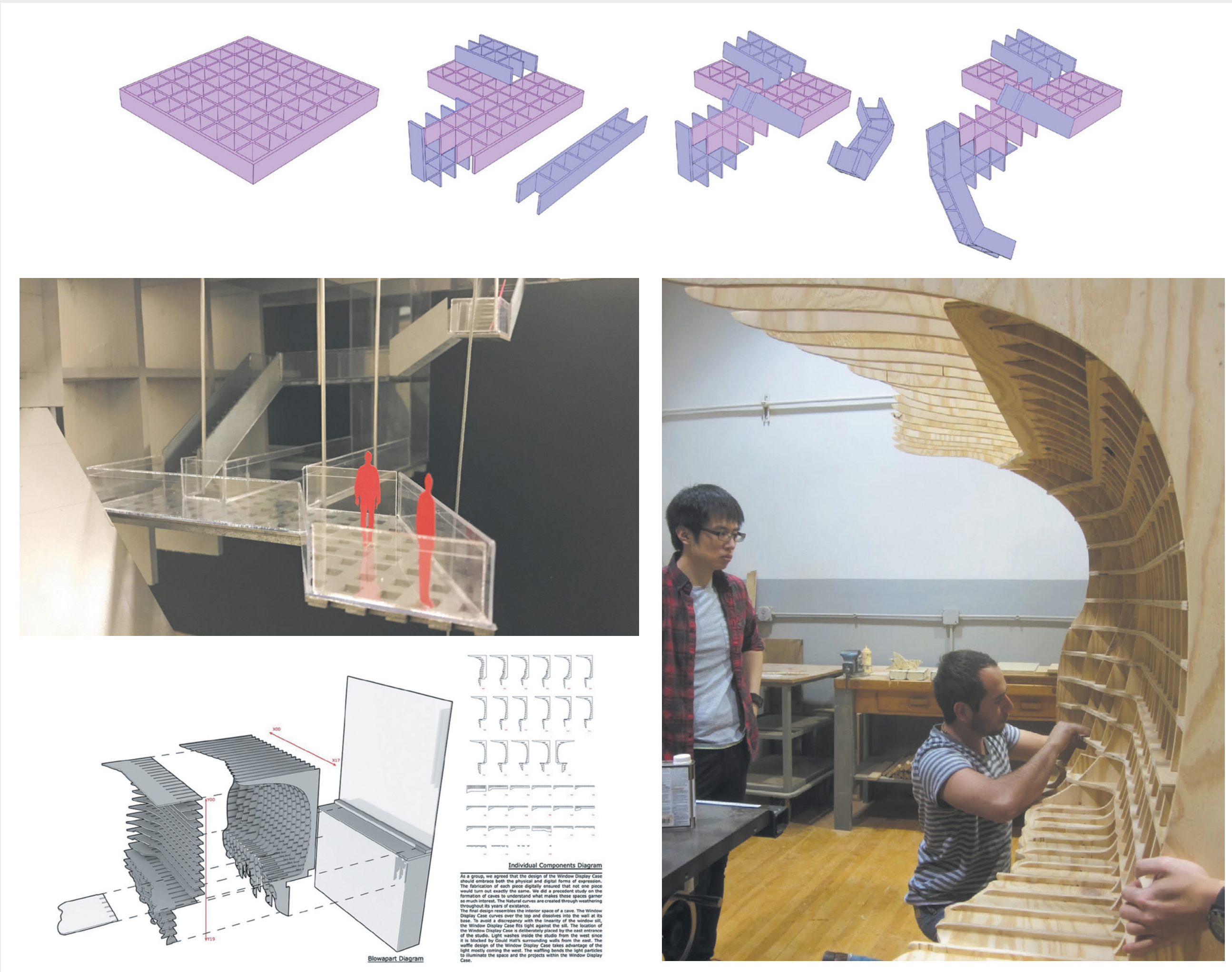


Figure 3. *Examples of two projects addressing a rectilinear grid at different scales.* ***Top*** *and* ***center left****: reimagining 24" × 24" wood space couplers/acoustical diffusers typically used in recording studios into an inhabitable grid (****red figures****).* ***Bottom left*** *and* ***right****: students developing a sculptural tectonic construct to provide acoustical diffusion at a prescribed window location.*

model into reimagined constructs within its surroundings. Both projects in **Figure 3** reference a grid, but the results differ in relation to how sound interacts with occupants. Students also develop design concepts through the lens of the COTE measures that include categories applicable to acoustics. Students have also packaged course projects into submittals for student competitions, resulting in local and national recognition by the AIA.

Acoustic Elective and Independent Study Courses

The Sound of Shaped Space, a reoccurring acoustic elective General Education course for upper division undergraduate and graduate students of various majors, has been offered periodically since spring 2011. This course began from previously developed topics and objectives during my adjunct positions at the University of Florida, Gainesville, and Kansas State University, Manhattan, dating back to 2004. It grew from an interest to share acoustical theory, vocabulary, applications, and the relationship to architectural space through material selections, MEP systems, environmental noise, and precedent projects with students. Students have enrolled in the course based on previous student word of mouth, hearing about the course from their advisor, or an interest in learning more about acoustics after having me as a previous professor or project reviewer. The course has been composed of a variety of different major and minor areas of study across the university and provides a welcomed diversity of experiences and thought, especially in how student interests may lie in acoustic categories other than simply architectural acoustics. Majors have included premed, architecture, interior design, environmental design, and architectural engineering, whereas minors have included history, literature, sociology, chemistry, geography, mathematics, anthropology, computer science, foreign languages, business management, and construction management that make the pedagogical approach unique. This course has also led to several students enrolling in independent study courses for advanced content. The mix of interests has led to successful team projects, presentations across campus and at conferences, involvement in various aspects of the Acoustical Society of America, and Newman Fund medalists.

The students experience acoustics through sound pressure level (SPL) and RTA measurements (**Figure 4**), local and regional field trips, and talking with design professionals and consultants about real-world conditions. The lessons learned allow opportunities applicable to current academic and future professional projects. Historical accounts and lessons learned over time include Greek and Roman theaters, Chladni plates, Martinville's 1860 phonautograph, Edison's wax cylinders, Sabine's vast contributions, the 1929 Noise Abatement Commission, and Robert Newman's recorded lectures from 1970.

We also review research and learn how good acoustic design improves student behavior because over 90% of classrooms exceed maximum background noise levels (Wang, 2013) and students miss up to 50% of what teachers say (Harmel, no date). When reading published resources, students also find relationships between the aural environment and personal productivity, retention, performance, and stress. In his book *Daylighting, Architecture and Health: Building Design Strategies*, Boubekri (2008) associates poor acoustics with various other issues contributing to sick building syndrome. We discuss various topics, including anechoic chambers and psychoacoustic research; acoustic marvels where specific frequencies believed by biobehavioral scientists relate to mood, empathy, and social behavior; restaurant acoustics; mechanical noise; electronic architecture to create various acoustical environments; and technological advances, including wireless charging where ultrasonic frequencies charge electronics. We carry a drum kit around to various places where students volunteer to activate the spaces and foster conversations about frequency interactions.

We also talk about acoustical versions of standardized materials such as a perforated metal deck that allows some frequencies to be absorbed in the roof insulation. Studying spaces with resonant pockets, cavities, and slots allow students to connect patterns, rhythms, and cultural or religious meanings to acoustical results. Students love learning about odd or unusual ways in which people have gathered information, including the use of war tubas and sound mirrors during wartime conditions prior to radar. We study the history of microphones and loudspeakers, including how public opinion originally thwarted full-range loudspeakers due to what was believed to be unnecessary frequencies. Students are also really surprised to hear there are loudspeaker systems well in the multiple

Figure 4. *Examples of memorable learning moments.* ***Left:*** *students investigating the floor isolation of ETS-Lindgren's Cedar Park, Texas hemianechoic chamber.* ***Right:*** *students surprising a motorcyclist leaving a campus parking garage as they enthusiastically approach with handheld sound pressure level meters.*

hundreds of thousands of dollars. A course favorite is the Radio Craftsmen (1957) Xophonic bookshelf speaker that housed 50 feet of plumbing tube/hose to create time-delayed reverberant energy.

It is always wonderful to introduce students to the world of cymatics, visualizing sound waves through different media. Ernst Chladni is credited with discovering the node and antinode patterns from frequencies induced in a plate covered in salt or sand, but credit is also due scientists such as Leonardo da Vinci, Galileo Galilei, Robert Hooke, and Sophie Germain. We might not see sound likened to not seeing wind, but we see the effects of the wind. Online videos of Schlieren photography catch students' attention because the rippling of sound waves are visible. Although we don't dive deep into human anatomy, we discuss the basics of the ear to understand how vibrations are translated and energy is converted into something understandable. An opera singer hitting certain frequencies and breaking a glass has some form of cool factor, but it's surprising to students to learn of the modulus of elasticity as the glass is wobbling in a slow-motion video just before the modulus of rupture. The cornstarch monster is fun to demonstrate (see youtube.com/watch?v=kevqQHZSeao), but I have destroyed a few speakers in the process. Students have also expressed interest in the cultural-, social-, and gender-related aspects of stereotypes and damaging effects of "vocal fry."

Although most students don't recognize David Byrne as the lead singer of the rock band Talking Heads, they like hearing about his collaboration with some other artists and musicians to activate spaces known as "playing the building" (Byrne, 2005). People pressed keys on a modified organ to trigger solenoids and hammers connected to beams, sprinkler lines, and pipes to reveal the aural personality of the space through the direct and reverberant energy. The space was activated beyond its typical occupancy and made us question if the result was noise, art, music, or a combination. This helps introduce an assignment to design and build a homemade instrument with found materials.

Sonic deception is also a hit with the students. What is known as the Ghost Army (The National WWII Museum, no date) strategically placed inflatable tanks and amplified wire recordings up to 15 miles away from enemy lines during World War II. The sights and sounds were convincing and successful. On another note, who knew water could be bent with low-frequency sound waves, sound deprivation therapy tanks exist, fire could be extinguished with low frequencies, or conversations could be captured through vibrating glass? Thank you, inventors and scientists who disseminated them.

I use photos and videos of places I have visited as teaching tools. Musikverein in Vienna, Austria, is always referenced due to its articulation, shoebox-shape proportions, and how people experience the natural acoustics. Every New Year's Day, the audience chairs are removed and stored in a cavity below the floor for the annual ball, which means the audience is typically sitting on what could be likened to an acoustic guitar resonant chamber. Notre-Dame du Haut in Ronchamp, France, emphasizes the binaural characteristics between proximity to the faceted/chamfered/splayed heavy concrete wall versus the opposing planar wall. Other examples include Myerson Hall in Dallas, Texas, and KKL in Lucerne, Switzerland, which are both flanked by an operable reverberant chamber and overhead canopy. There are sectional models of the Paris Opera House that help convey how distance and layers nestle the performance area away from the street noise and deep within the confines of structure. Red Rock Amphitheater in Colorado and 333 Feet Underground in Tennessee provide examples of rock formations resulting in diffusion and envelopment. These examples help tie conversations about materials, distances between stage and audience, and number and slope of seating to historic Greek and Roman architecture.

Research and Practice: Demonstrating Principles into Reality

In addition to teaching students through traditional courses, I demonstrate and practice those principles through funded research, publications, service-learning design-build projects, and professional practice. The advancement of knowledge through pedagogy stirs student and community interest into tangible and measurable physical results. The active process of creating and making results in real-time design to occur while developing both small and full-scale prototypes. The teaching tool is simple: students not only see but also hear the connection between materials and the resultant environment, weaving acoustics and aesthetics together. I also share professional projects where I have been architect and/or acoustical consultant, including collaborations with other firms. These new and adaptive use projects show future generations methods of implementing concepts into practice and learn from lessons in the field (**Figure 5**).

Figure 5. ***Top:*** *palette of interior finish materials shared in the classroom to teach color, texture, and related acoustical properties prior to experiencing spaces in person.* ***Bottom:*** *students visiting the Booker T. Washington High School for Performing and Visual Arts recording studio in Dallas, Texas, with Russ Berger and Richard Schrag, to teach audio production. The field trip allowed the relationship of theory and principles as students asked questions about stretched fabric, sloped laminated glass, and infrastructure/routing such as microphone inputs, isolated grounds, and rack equipment.*

Court Appointed Special Advocates Playhouse

Within an intensive three-week summer course, students were tasked with designing and constructing a playhouse to be raffled at a local mall to benefit Court Appointed Special Advocates (CASA). This opportunity provided a seldom-offered model where the course included students from multiple-year levels. They learned how design decisions based on modularity, transportability, and available materials resulted in specific acoustical properties. Seated children in the lower space hear their voice reflected back in an additive manner due to the twisting and stepping of the cedar, cypress, and acrylic layers. Similarly, this project embodies the essence of "undergraduate courses in acoustics for a School of Architecture." Marshall (1963) states the relationship between acoustics and a design process must be identified "first in terms of the process, and second in terms of the aesthetic judgments which by definition are integral with 'design.'" The playhouse demonstrated acoustical results of materials and shape through immersive learning (**Figure 6**).

Stabilized Compressed Earth Block

A collaborative multidiscipline team of OU students and faculty explored earthen design and construction techniques through an elective course that led to an Environmental Protection Agency (EPA) P3 Award and Grant. The team then partnered with Cleveland County Habitat for Humanity (CCHFH) to design and construct a stabilized compressed earth block (SCEB) residence and a conventionally wood-framed version of equal layout, area, volume, apertures, and roof structure on an adjacent site. Through both laboratory

Figure 6. ***Left:*** *students and faculty designed and built the playhouse in the University of Oklahoma Gibbs College of Architecture Creating_Making Lab.* ***Center:*** *delivery and installation of the playhouse to the raffle winner's property.* ***Right:*** *child climbing the interior stepped and faceted enclosure also responsible for the acoustical results.*

tests and field validation, researchers demonstrated the structural, thermal, economical, and acoustical values of SCEB as a viable residential building material.

Interactive Synchronicity

Another small group of students designed, constructed, and calibrated an inhabitable interactive installation based on the Buskuhl Gallery space in the OU GCA Gould Hall's lively acoustics and outward display to campus, employing excessive reverberation time and resonance as a method of visually demonstrating the persistence of sound waves. The amalgamation of materials and acoustical sensors defined the visual translation of acoustical impulses into rhythmic patterns and textures of light. People quickly realized the lights were triggered by airborne impulses such as voices or laughter, and impact impulses such as footfall or slamming doors. They equated continual light flutter to lingering impulses outside human perception. Some participants were instantly provoked to make more or specific sounds to cause illumination, whereas others attempted to cease the dancing lights. People physically inhabiting the space were the participants and critics, not by their words as comments in a formal jury setting but by their real-time reaction to their personal interaction.

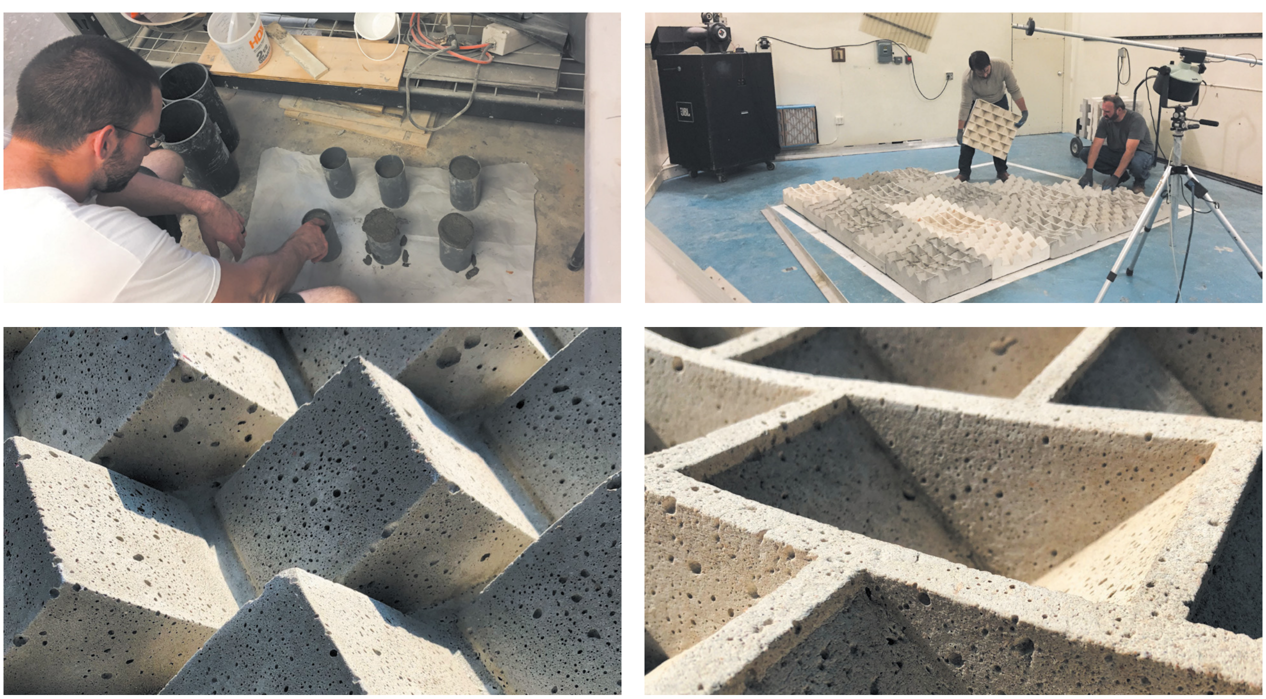
On Display

Students have also constructed instruments and loudspeakers as part of an assignment or as an expression of their interests to unite acoustics and craft into particular listening environments. A disabled veteran student who is legally deaf in one ear created loudspeaker enclosures linked to a wall stud cavity that was displayed at a local art gallery. The wall cavity between framing members and the wall finish was part of the installation, thereby actively integrating acoustics into architecture. People were able to hear and experience what the student created related to an occupied space. It was not just theory but was demonstrated through creating and making.

Acoustically Diffuse and Absorbent Lightweight Aerated Concrete

Students in the spring 2017 acoustics elective course began the initial process of basic data collection that led to prototypes, modeling in various software applications including EASE, feasibility studies, and compiling

Figure 7. ***Top left:*** *student developing concrete mixes in various size compression strength test cylinders.* ***Top right:*** *student placing acoustically diffuse and absorbent lightweight aerated concrete (ADALAC) panels in the Riverbank Acoustical Laboratories reverberation chamber.* ***Bottom:*** *close-up photographs of both the sawtooth (**left**) and recessed (**right**) prototype panels showing shapes and surface porosity responsible for reflection, diffusion, and absorption.*



applicable precedent studies. I led a team of students to evaluate the frequently occupied Buskuhl Gallery space as a test bed for acoustical research. The data-driven design process allowed students to measure and understand quantifiable values beyond anecdotal opinions and related occupied space with acoustical criteria. Undergraduate and graduate students worked with me to evaluate space through the collection of acoustical data that then fueled the development of material science as the vehicle to address deficiencies. The resultant acoustically diffuse and absorbent lightweight aerated concrete (ADALAC) prototypical panels (**Figure 7**) combine the atypical use of concrete to employ reflection, diffusion, and absorption in typical speech frequencies, yielding substantial increases in laboratory- and field-measured acoustical values (Butko, 2021). This project introduced and bolstered various phases of architectural acoustic principles and led to expanded collaboration with other colleges and another university.

Summary/Conclusion

Architecture is a tapestry of theory, intent, and realism hovering somewhere among the poetic, the technical, and the material, resulting in improved health, safety, and welfare of occupants. Participants begin to understand materials, shapes, room volume, and programmatic adjacencies as interdependent and symbiotic entities. Students, and occasionally clients, typically don't know what they don't know. The process of introducing acoustics opens their eyes and ears to more of the various aspects of architecture. I hope this article has inspired you in some manner either to have a new interest in acoustics or perhaps to open the door to an aspect that you would like to explore further. Everyone can learn and has some outlet of educating others.

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Daniel Butko, an architect and Associate Professor of Architecture, has academic and professional experience spanning over 30 years in all phases of design, client management, construction administration, and consultation focused on architectural acoustics, material science, and data-driven design. Notable achievements include an Environmental Protection Agency (EPA) P3 Award, a Disney Dreamers and Doers Award, an Acoustical Society of America Rossing Prize, an Architect Magazine R+D Award, American Institute of Architects and American Concrete Institute awards, and advisor to award-recognized student projects. Daniel's teaching career has allowed instruction to over 1,500 undergraduate and graduate students.

Weird Data: The Element of Surprise in Underwater Acoustic Sensing

Erin M. Fischell

The Challenge of Underwater Acoustics

Dive underwater and the world changes. The color you see shifts toward blue green, your ears pop and fill with water, and suddenly things sound different (e.g., Casper et al., 2022). The splashes and bird calls above the waves disappear and are replaced by groans, clicks, and pops (Dahl et al., 2007). What are these sounds? Where do they come from?

Or maybe you are on a boat over a trench thousands of meters deep. Suddenly, the depth sounder seems to think that the water is only 500 meters deep, but the chart says it should be 5,000 meters. The instrument jumps from 500 to 5,000 meters and back for a few minutes and then settles. What happened?

The commonality between a boat's depth sounder and those mysterious sounds you hear when you dive beneath the waves is underwater acoustics, a field in which even the most experienced practitioners struggle with understanding all of the many sources of interference, noise, and changing physics needed for data interpretation. Users of ocean acoustic instruments don't control whale calls, shipping, snapping shrimp distribution, fish finders on other vessels, nesting creatures, or pile driving and cannot predict ahead of time all of the possible sources of interference in acoustic data. The complexity of underwater acoustic systems provides further challenges; is that unexpected signal a new source in the environment, a potential signal of interest, or system noise?

This complex interaction of environment, uncontrolled and uncorrelated noise sources, internal noise sources, and unexpected reflections leads to a lot of "weird data" in underwater acoustics. These weird data are the segments in any underwater acoustic time series that don't answer the fundamental questions at the core of the experiment or are mysterious in origin.

Humans are driven to find patterns in the chaos and to try to understand the whys and wherefores of our world. Everyone experiences trying to understand weird sound data in daily life. For example, you might hear an unexpected squeak or beep at home and spend a few minutes walking around the house, turning your ears in different directions, sticking your head out windows, and pausing to listen, all to try to find the noise source. Or perhaps you apply sound pattern recognition while trying to diagnose a suspicious rattle in a car engine, pressing the gas pedal and then the brake, querying your partner to determine if the sound got quieter or louder with the change of variables.

The quality of underwater acoustic measurements constantly changes based on uncontrolled, capricious factors. Therefore, interpretation of underwater acoustic data is like hunting that unexpected squeak, groan, rattle, or flutter, generally without the benefit of being able to stick your head out the window or adjust self-noise to see if the sound is still there. This sometimes frustrating process is the quintessential center of science: taking in the unexpected and using that new information to question the foundations of knowledge. There is a lot to be learned by our weird data, and in surprises that provide insight into systems, biology, and oceanographic processes in the ocean.

Categories of Interference

Surprises in underwater acoustic signals occur when our a priori understanding of the environment, ambient-noise sources, and the paths of transmission of acoustic energy are incorrect or incomplete. The ocean environment is stochastic in nature (Colosi, 2016), with properties of both signal and noise varying constantly in ways that are difficult to predict (Miksis-Olds et al., 2018). Understanding underwater acoustic data becomes difficult when the

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noise level is higher or when the signal level is lower than expected. The objective of this article is to show examples of these categories of interference and provide some stories illustrating how they were diagnosed.

These underwater acoustic surprises fall into four general categories:

(1) External sources: acoustic energy from nonsignal sources in the environment;
(2) Environmental propagation effects: changes in transmission loss between the receiver and the source due to sound speed and boundary effects;
(3) Internal system noise: sources within a system such as mechanical vibrations, electrical interference, crosstalk, flow noise, and self-noise; or
(4) Unexpected reflection: reflection and scattering from water column sources, (e.g., ships, volume inhomogeneities, thin layers, organisms).

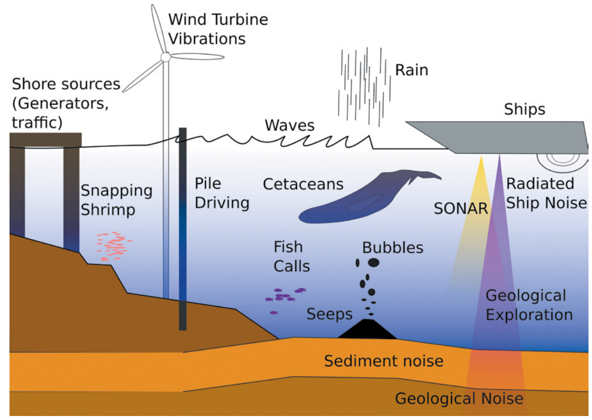


Figure 1. *Examples of external interference that may be picked up by a receiver in the ocean. These sources are uncontrolled, and many often occur together to emit sound at varying frequencies into the water that can affect underwater acoustic sensing systems.*

External Interference

Sound is emitted into the water by a wide variety of anthropogenic and natural sources (Bradley and Nichols, 2015), and it is the resulting "external interference" that comes to mind when most people think of underwater noise. **Figure 1** shows a few of the many sources of external interference for acoustic systems in the ocean that result in noisy underwater acoustic data.

The background noise level in the ocean is often approximated as a single decibel number based on sea state, weather, and frequency/prevalence of shipping. Although this ambient noise estimate is an approximation of the ambient-noise level, the geographically and temporally variable true ambient noise in the ocean is far more complex. Weird data due to external interference occur when noise levels exceed expectations and/or vary significantly with time. Sources of this type of "surprise" external interference in underwater acoustics might include natural sources of sound (e.g., cetaceans, fish calls, snapping shrimp, noise from weather, waves, or geology) and anthropogenic sources of sound (e.g., ships, sonar systems, acoustic modems, pile driving, or airguns).

Natural Noise Sources

Biological noise sources can cause significant problems with autonomous processing or detection methods because cetacean communications are often in the same frequency band used for underwater communication and navigation systems. Matt Palanze of the Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts, experienced just how challenging it can be to operate acoustical systems in the presence of marine mammal noise when his team was attempting to trigger an acoustic release:

> "On an OOI cruise, we approached a large surface mooring for recovery. We communicated with the acoustic releases with a deck box located in the ship's lab. There are three releases on this mooring, two are connected in parallel for redundancy, specifically in the case of a failure. We can release the other with no other intervention being needed. None of the releases would reliably respond to queries and commands; there is a very low historical probability of this occurring. After approximately 20 minutes (which, as you know, is forever in ship time!), one of our colleagues came into the lab and announced, 'There's about a thousand dolphins out there!' We went out on deck, and sure enough, there were dolphins and whales to the horizon. We could hear their calls from the deck. We had to stand by for an hour or so until the pods moved on. After that, we released the mooring and recovered as normal. I believe this event went into the cruise report as 'Operations delayed due to Mammalian Interference'" (personal email, 2022, used with permission).

Dolphins and whales are not the only creatures that can create external interference for acoustic systems, as Emma Cotter of the Pacific Northwest National Laboratory, Richland, Washington, experienced with a passive acoustic data recorder in the ocean:

> "When we deployed an autonomous system, the hydrophone data showed periodic sound at low frequencies (<1 kHz) that we couldn't explain. We initially thought it might be electrical noise or flow noise, but eventually realized it was the result of crabs scraping their carapaces on the metal surfaces of the lander" (personal email, 2022, used with permission).

Another common biological noise source is snapping shrimp. When these extremely loud, impulsive signals are present, they can significantly affect the acoustic system signal-to-noise ratio (SNR) in frequency ranges from low kilohertz to 10s of kilohertz. If you ever go scuba diving, you might hear the signal from snapping shrimp as a crackling high-frequency sound near reefs.

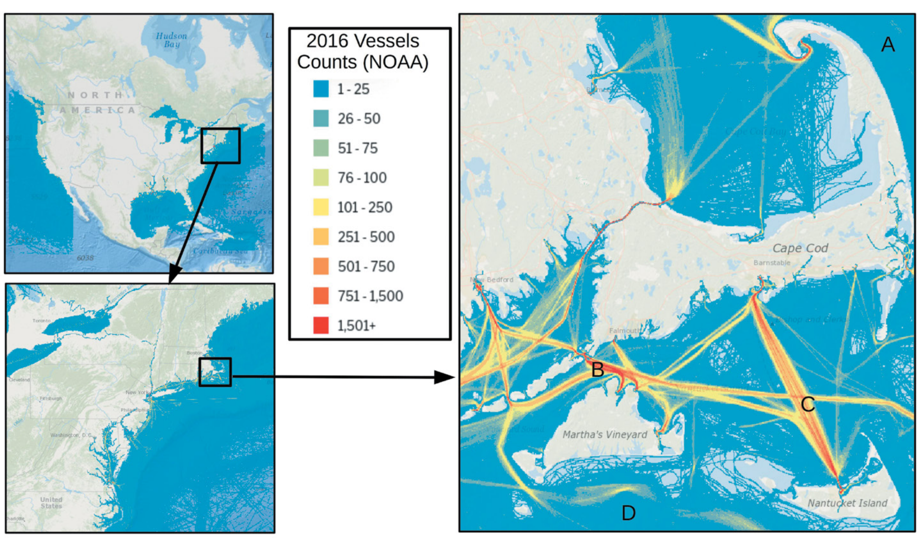
In addition to biology, the ocean environment itself is a source of natural external noise. Examples include sea ice (Worcester et al., 2020), glacial action (Deane et al., 2019), sediment noise, surface weather and waves, magma displacement, and earthquakes.

Anthropogenic Noise Sources

The actual noise level due to shipping is highly linked to latitude, longitude, and depth relative to strong propagation paths from shipping lanes. Worldwide automatic identification system (AIS) maps are available that show historical counts and densities of ship traffic, revealing striking patterns in ship movements. **Figure 2** shows an example of one of these maps from 2016 for the waters around Massachusetts using publicly available National Oceanographic and Atmospheric Association (NOAA) data. Unsurprisingly, choosing a sensor location near a shipping channel or ferry route significantly increases the ambient-noise level due to ships (e.g., B and C in **Figure 2**), whereas a location with only a few ships per year (A and D in **Figure 2**) will have a much lower noise level due to shipping.

The impact of nearby boats on an instantaneous SNR is striking when seen in a spectrogram or beamformed passive acoustic data from an underwater hydrophone array. **Figure 3**, *top* and *bottom right*, shows the results of a boat crossing near an array of recorded acoustic data. Ship noise is complicated because it overwhelms most other signals, is aspect (angle) dependent, and is subject to Doppler shift and multipath effects; this causes an interference pattern that shifts in frequency with range

Figure 2. *Automatic identification system (AIS)-based ship counts from National Oceanographic and Atmospheric Association (NOAA) for 2016 around Cape Cod, Martha's Vineyard, and Nantucket Island in Massachusetts. Geographical location in the ocean has a large impact on the ambient-noise level. For example, a sensor located at point A or D would experience far lower noise from ships and boats than a sensor at a location experiencing multiple times daily ferry traffic (point B or C).*



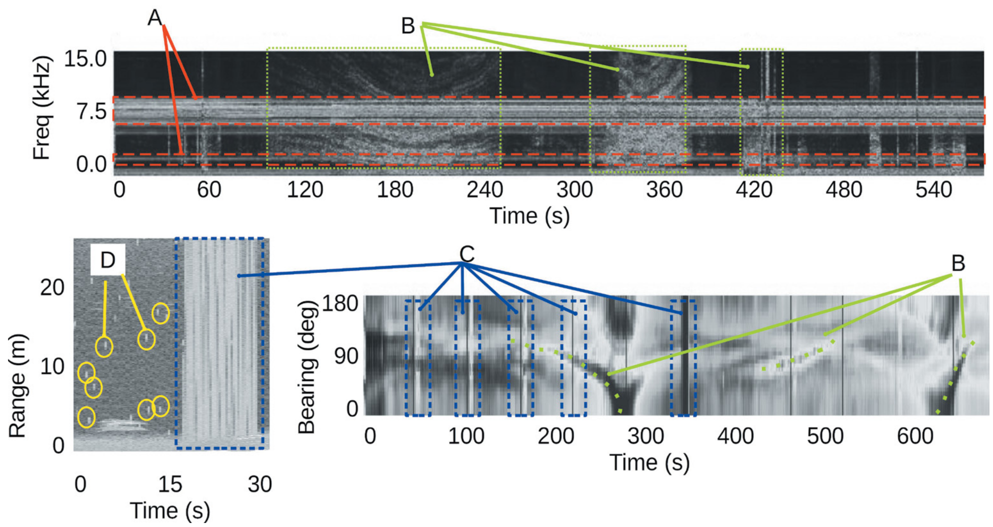


Figure 3. *Examples of interference in acoustic data. All plots show grayscale decibel levels of received power.* ***Top:*** *spectrogram of passive acoustic data. Significant features of the spectrogram include ship noise (point B) and broadband electrical power noise (point A).* ***Bottom left:*** *broadband echo sounder data that include acoustic modem noise (point C) and acoustic Doppler current profiler (ADCP) interference (point D) that obscures scattering from water column features.* ***Bottom right:*** *beamformed acoustic array data indicating the direction of arrival (bearing) in degrees of energy versus time. Ship transects are visible and change in bearing versus time (point B). Acoustic modem noise is also present in the bearing color plot (point C,* ***vertical dashed lines****).*

(Gassman et al., 2017; Miksis-Olds et al., 2018). Other common sources of anthropogenic noise include airguns, pile driving, wind turbine noise (Amaral et al., 2020), and vibrations transmitted through other types of structures (e.g., traffic near a dock, oil platform vibrations).

Given the prevalence of anthropogenic noise, and ship noise in particular, many researchers have been working over the last decade to use these "sources of opportunity" to better understand the ocean. This includes gleaning estimates of biomass in the ocean (Haris et al., 2021) and temperature and salinity (e.g., Kuperman et al., 2017) via a process known as acoustical tomography.

Environment Propagation Effects

The underwater environment includes the surface, water column, and bottom. Received acoustic signals in the ocean are affected by all three. In all underwater acoustics, the received signal is affected by transmission loss, which is the spread and attenuation of the source signal by environmental factors and absorption. In the simplest estimate of transmission loss, a line is drawn between a source and receiver, and the received amplitude is calculated as the source level minus the geometric spreading loss (spherical and/or cylindrical) and absorption (Francois and Garrison, 1982).

Although this would be the approximate case for a uniform sound speed profile, sound in the ocean curves, is reflected, and gets trapped based on boundaries and sound speed versus depth, range, and time. In all these cases, an essential fact of underwater acoustic propagation is that temporal and spatial changes in the surface, bottom, and sound speed impact instrument measurements.

Boundary Effects

Boundary effects, such as sound bouncing off the surface, the bottom, and ice, are illustrated in **Figure 4**. Surface, ice, and bottom interactions all can cause scattering, reverberation, and reflection. The resulting signal multipath varies significantly based on surface and bottom roughness and slope or from jagged features of the ocean bottom. Additional boundary effects are driven by the fact that the ocean seabed is not homogenous; layering is common, with changes in density and sound speed causing reflections and changes in the signal.

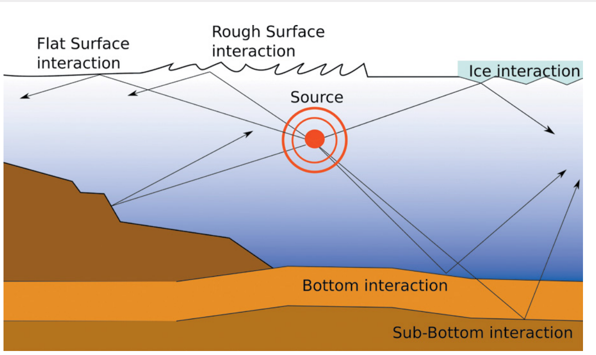


Figure 4. *Interactions with the surface and bottom change acoustic propagation. The ocean surface and bottom can have varying roughness. Ice on the surface can also cause reflections. Layering in the ocean bottom can also cause subbottom reflections.*

Bottom topography, in particular, can cause acoustic arrivals at the receiver from unexpected angles, at large intensities and unexpected time delays. Peter Brodsky of the Applied Physics Laboratory, University of Washington (APL-UW), Seattle, described a particularly startling reflection he experienced:

> "Years ago (many) I was on a Navel Oceanographic Office ship — the USNS Lynch — performing seismic surveys in the South Atlantic. Our typical acoustic sources were airguns and sparkers, but in really deep water we'd use explosives. On one occasion we dropped a final charge, heard it go off, then went off to get dinner. A minute or so later there was a BIG bang that shook our soup bowls in the mess. The Chief Engineer (CE) ran out and raced down to the engine room, cursing about some incompetent oiler who let the engine throw a rod (again). Turns out it was a reflection of the last charge off a submerged ledge of some kind; far away but oriented perfectly to direct the sound right back at us. The CE never showed up at regular mealtimes again" (personal email, 2022, used with permission).

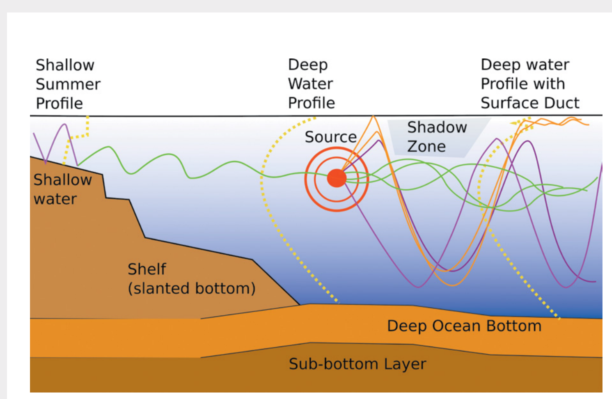
Volume Effects

The second major impact of the underwater environment on propagation is that sound energy refracts (i.e., curves) due to changing sound speed with depth and range. This creates convergence zones, shadow zones, ducted sound, and long-range propagation of low-frequency energy. **Figure 5** shows some of the ways the sound speed profile affects the refraction of sound in the ocean. Sound curves toward a lower sound speed, and this causes the complex behavior observed in ocean propagation. This includes SOFAR paths (**Figure 5**, *green*) that are refracted above and below to channel around the sound speed minimum, deep convergence paths (**Figure 5**, *purple*) that are caused by steeper launch angles and refract at deeper and shallower points than the SOFAR paths, surface ducts (**Figure 5**, *orange*) where a local sound speed minimum can trap sound near the surface, and downward refracting profiles that commonly cause increasing bottom interaction and signal attenuation in shallow water. Another feature of environmental ocean propagation is the creation of shadow zones where little energy is received due to the bending of rays.

Changes with Time

Fading of signals and/or amplification of noise due to changing environmental conditions is another common underwater acoustics challenge to signal interpretation. Temporal variability in sound speed is caused by submesoscale to mesoscale (i.e., 1-100 km) variations in temperature and salinity, such as eddies, warm core rings, internal waves, and buoyancy fluctuations (Colosi, 2016).

Figure 5. *Examples of volume propagation effects due to sound speed changes with range in the ocean. Three different sound speed profiles are shown (**yellow dotted lines**): a summer shallow-water sound speed profile (**left**), a deepwater sound speed profile (**center**), and a deepwater sound speed profile with a surface duct (**right**). **Green**, so-called SOFAR or deep sound channel paths; **purple**, convergence zone (cz) paths; **orange**, convergence zone/surface duct paths; **magenta**, downward-refracting paths that result from a shallow-water summer sound speed profile; **gray box**, shadow zone where little acoustic energy is received.*



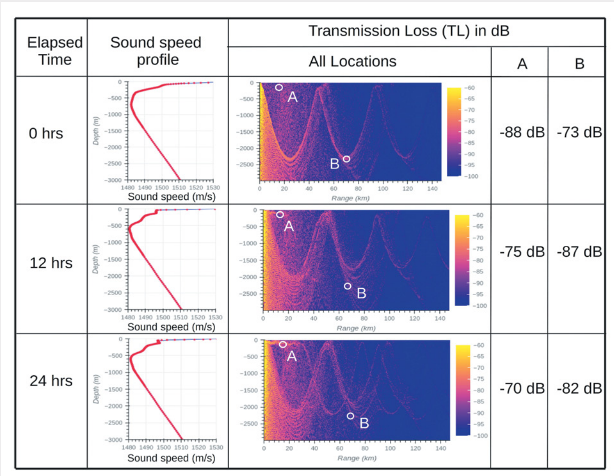


Figure 6. *Example of sound speed evolution versus time and the associated change in transmission loss (TL) for deepwater. At 0 hours, the profile is a conventional deepwater profile, with no surface ducting and a deep convergence path (**top**). After 12 hours, a surface duct begins to form, with a decrease in transmission loss at point A and increase in transmission loss at point B (**center**). After 24 hours, the surface duct is fully formed for an additional decrease in TL at point A (**bottom**).*

One example of an environment changing with time is currently being studied in the Arctic Ocean, where an intrusion of warm salty water in the Beaufort Sea is creating a sound speed minimum around 200 meters that is significantly impacting use of acoustic communication and navigation systems (Worchester et al., 2020). Shorter timescale changes in acoustic transmission occur due to buoyancy fluctuations, tidal effects, and internal waves. **Figure 6** shows how propagation characteristics can also change significantly over just 24 hours. For the same geographic location, small changes in the ocean sound speed versus depth (i.e., the "sound speed profile") have a profound effect on the resulting transmission loss versus range and depth over several days. The resulting fields are qualitatively quite different for an identical source depth of 100 meters when the sound speed profile has changed with time due to a passing eddy.

Internal System Noise

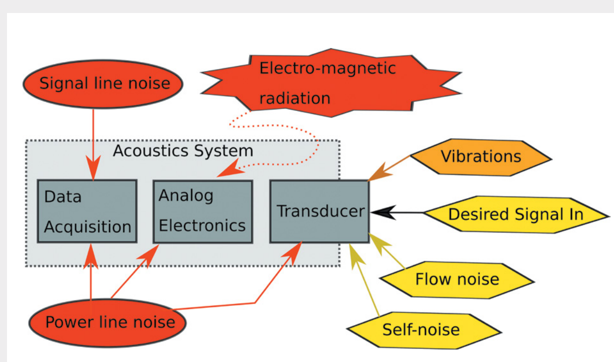
Internal system noise plagues underwater acoustic systems. **Figure 7** shows how electrical noise, vibrations, and through-water system noise (e.g., flow noise and self-noise) couple into an acoustics system composed of a transducer, analog electronics, and a data-acquisition system. Most of these noise sources are related to the fact that acoustic instrumentation is generally deployed on a platform (e.g., a vehicle, vessel, or mooring) with moving parts, power systems, and/or communication systems.

Self-Noise and Vibrations

Passive and active acoustics systems are often mounted on some kind of vehicle, and it is common to have multiple sonar systems in use at a single time on a single vessel. This leads to vibrations, flow noise (due to motion through the water), and self-noise (due to acoustic sound put into the water by the vessel itself and/or pinging acoustic systems onboard). Christopher Bassett of the APL-UW experienced this type of ship noise, with a mystery signal that persisted across multiple sonar systems:

> "Working on a hydroacoustics survey we encountered a cyclical noise issue that caused significant drops in signal to noise ratios (SNR) across numerous narrowband echosounders. This noise would appear somewhat randomly even when the vessel operating conditions didn't change. Fortunately, the vessel had hydrophones installed and we were able to observe that periods of low SNR corresponded to times when elevated noise levels were observed. The hypothesis was that this was attributed to an issue with the bearing that produced a crunching sound tied to the prop's rotation rate, which was consistent with the mechanical nature of the sound and the temporal structure of the measured noise. Following time in dry dock, the noise ultimately disappeared, suggesting we were

Figure 7. *Typical sources of internal system noise in underwater acoustics. **Red**, electrical noise sources; **orange**, structurally coupled vibrations; **yellow**, acoustic (through-water) signals; **black arrow**, desired signal input, also a through-water signal.*



on the right track and that the faulty bearing(s) ultimately played an important role in the degraded data quality on a commercially important acoustics survey" (personal email, 2022, used with permission).

As an example of co-interference of active acoustic systems, an acoustic modem, acoustic Doppler current profiler (ADCP), echosounder, and passive acoustic array may all be used at the same time on a single platform. In **Figure 3**, *bottom left*, interference from a 20-kHz WHOI micromodem shows up in a 333-kHz echosounder; the ADCP signal is also seen in the echosounder data as single-time specks with varying range. In **Figure 3**, *bottom right*, interference from a 20-kHz WHOI micromodel also affects bearing estimates in a target-tracking problem, showing up as strong cross-bearing features in beamformed passive acoustic data.

Electrical Noise

One of the biggest challenges to designing and building any effective acoustics system is electrical noise. In underwater acoustics, electrical noise problems are exacerbated by the restricted space in the required waterproof enclosures so that noisy components are generally physically nearby noise-sensitive elements. Furthermore, the limited pins available on underwater connectors often result in combined ground lines and limited sensor isolation. Those same underwater connectors are notorious for degrading signal quality.

As a result, underwater electrical systems need to be designed extremely carefully to ensure isolation between noisy and sensitive components. One common issue is the sensitivity of underwater acoustic systems to the resonances of platform power sources and loading on a power system; a system with low noise plugged into a ship laboratory when the ship is running on battery can experience a sudden high-noise floor with severe narrowband frequency interference when the ship's generator kicks in. Another challenge arises from other sensors or systems in use on the same platform. It is extremely common to locate multiple acoustic systems on the same platform with the same power system. Active acoustic systems can interfere with recordings on a different acoustic sensor acoustically through sound put into the water, through the power system, through electromagnetic interference, or through signal ground lines. Other systems, such as actuators, radio communication systems, and spinning drives, can also create a combination of acoustic, vibration, power, and signal noise that interferes with most acoustic sensors. Any active voltage converters can also create interference that impacts acoustic data recordings (**Figure 3**, *top*) where a significant part of the spectrogram is obscured by power system noise). These issues should be taken into consideration when designing, building, and deploying systems and when analyzing data.

Unexpected Reflections, Scattering, and Clutter

Sound is used to explore the ocean because it provides so much information, but sometimes that information is difficult to understand. Unexpected reflections and scattered sound are another source of surprises in underwater acoustic data. The most frequent issues caused by unexpected reflections are signal saturation, false positive detection, or confounding between the "signal" targets you want in your experiment and other targets ("clutter"). For example, in an experiment to count fish, an echosounder might show returns from fish but also returns from copepods, or changes in water density, shear instabilities, bubbles, and kelp (Stanton et al., 2021).

Man-made objects and structures also can cause unexpected reflections and scattering, even in the most controlled of experiments, as related by Aubrey Espana of the APL-UW when her team was running a seabed target-scattering experiment and found that a surprise ship reflection limited their working area:

> "During BAYEX14, a side lobe from our source reflected from the bottom of the boat. The timing of the path was such that it overlapped the 15m target line. So essentially, we couldn't put any objects out at that ground range. The boat was in a 4-pt moor, so moving it was not an option" (personal email, 2022, used with permission).

Reflections off boats, vessels, and underwater structures can have significant effects on sensing, navigation, and communication systems by presenting echoes that can confound the desired signal. Because acoustic systems are often mounted on some kind of platform, the platform itself can be a pernicious and difficult to identify source of reflection, as Nicholas Rypkema of WHOI observed firsthand:

"During the integration of an ultra-short baseline receiver (USBL) on an autonomous underwater vehicle, I spent a few frustrating weeks trying to figure out exactly why I was not getting the accuracy I was expecting. Eventually, I realized that the position at which the USBL receiver was located on the vehicle changed the accuracies that I obtained — ultimately, I discovered that local acoustic effects between the received signal and the body of the vehicle created extremely reproducible biases in the resulting angle estimate" (personal email, 2022, used with permission).

Biological factors are notorious for obscuring or changing expected returns in all types of active sonar systems; fish and plankton scatter sound so they often show up when they are not the object of measurement. This was observed by James Ian Vaughn of WHOI when mapping bottom topography:

"We were surveying the Kick'em Jenny volcano off the coast of Grenada with an EM302 multibeam some time ago. We saw a bunch of large discrete scatterers sitting in/over the caldera. We quickly followed up the multibeam survey with an ROV dive. Turns out the scatters were a school of large tuna. Too deep to fish for, unfortunately" (personal email, 2022, used with permission).

Hunting down the reasons for initially unexplained scattering and reflections has led to many revelations and discoveries across the ocean disciplines. A perfect example of this is the deep scattering layer. Early SONAR systems observed a so-called "false bottom" at around 500 meters deep. This scattering layer in the twilight zone of the ocean consists of enormous numbers of animals that migrate daily in depth, including fishes, squid, and siphonophores. Understanding this deep scattering layer has been a major objective in marine science and acoustics this decade because disruption due to fishing and deep-sea mining could have profound implications for both biodiversity and the global carbon cycle (Boscolo-Galazzo et al., 2021).

The Value of Weird Data

"Blink our eyes, and the world you see next did not exist when you closed them. Therefore, he said, the only appropriate state of mind is surprise. The only state of the heart is joy. The sky you see now, you have never seen before" (from the *Thief of Time* by Terry Pratchett).

The attitude of underwater acoustics users in relating tales of weird acoustic data is, indeed, joy mixed with some amount of chagrin. These incidents are clearly not isolated. And when organized into the categories illustrated in **Categories of Interference**, they begin to paint a picture of the types of interference any given system may experience in the ocean. Instead of simply filtering out these surprises, they can be treated as interesting and worth preserving, sharing, and publishing.

Over the last five years, there has been an increasing effort to centralize and process underwater acoustic data (e.g., Wall et al., 2021) and to share code and processing tips among the acoustics community. A great resource list of underwater acoustic datasets is maintained by the United Kingdom Acoustics Network and includes no fewer than 33 separate databases as of March 2022 (see acoustics.ac.uk/open-access-underwater-acoustics-data). Each database has different sensor characteristics in a mix of active and passive acoustics.

In terms of processing code, the development of MATLAB toolboxes and open-source packages in Python for underwater signal processing and array processing make sophisticated analysis of acoustic data far more accessible. There are also domain-specific efforts to connect community members for information sharing, such as a new Bioacoustics Stack Exchange (see acousticstoday.org/wPQmt), built to provide a centralized discussion space for conversations about processing and understanding bioacoustics data in particular.

Including specific identification and labeling of weird data within broader datasets and processing tools as a part of this community-wide effort feels both natural and necessary, for three main reasons. First, there is an incredible potential of "found data" for other researchers, where weird noise in one discipline can be identified as a signal by another. Second, cross-sensor, labeled examples of interference would pave the way for the use of machine-learning tools in the development of ubiquitous underwater acoustic classification tools for autonomous identification of interference sources. Finally, these types of tools would make underwater acoustic data interpretation significantly easier and would also provide more information about the oceans, feeding back into providing found data across disciplines.

A brilliant use of this type of fortuitous data was related by Arthur Newhall of WHOI:

> "Unexpected data can be useful. One of our colleagues ADCPs blew up underwater from a lithium battery leak during SW06 field work off NJ. We knew the exact millisecond that happened from our local data collection receivers there, so used it to calibrate Comprehensive Test-Ban Treaty Organization (CTBTO) hydrophones off the coast of South Africa" (personal email, 2022, used with permission).

The first step to seizing on opportunities like Newhall's is talking about our weird data and starting to develop categories and classifications. Automatic, cross-system identification of several of the types of interference listed in **Categories of Interference** would not be big lifts computationally but will require databases of examples across the many types of acoustic systems and, eventually, open-source filters. The basis of more community-wide libraries and labeled datasets of unusual observations might start with acousticians keeping a folder on their computer of screenshots and brief metadata on surprises. Why not leverage all that weird underwater acoustic data by sharing and identifying all the surprises that the ocean throws at us?

Acknowledgments

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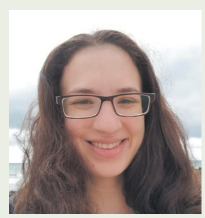

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Sounds Full of Meaning and the Evolution of Language[1]

Susanne Fuchs and Aleksandra Ćwiek

Imagine that you are a child again and smell fresh-baked cake when you come home after school. Maybe it's your grandmother's apple cake or your neighbor's famous cheesecake. You audibly inhale through the nose and your eyes roll because the cake smells delicious. You open the door. There is a piece waiting for you right there, still warm and fresh from the oven! You take a bite. Now, with this memory in place, how could you let someone experience it with you? You could try describing the taste with words. Maybe the cake is mild, maybe zesty, or maybe it's just delightful! However, it might be difficult to describe a sensory experience like that using conventional language.

A different way to describe the experience would be to use depictive rather than descriptive communication. You might do a breathy grunt followed by a long /m/. There can be yumminess all over your body, too: hands touching the smacking lips, eyes and eyebrows frowned in the sense of pleasure. An m-sound might be meaningless without the additional information of the situation, but producing "mmm" with the smell of one's favorite cake in mind clearly delivers the meaning of pleasure.

The intent of this article is to show that speech sounds can be much more than mere meaning-distinguishing units. Through established cross-modal correspondences with other sensory dimensions, human vocalizations can bear meaning that translates to a real-world context. We argue that cross-modal correspondences and the iconic resemblance between the audible form of spoken language and other sensory information create meaning and were essential to get language off the ground at its dawn. In this sense, the world of sounds can be full of meaning.

The World of Sounds

Traditionally, a speech sound (or phoneme in linguistic terms) is the smallest meaning-distinguishing unit of speech. For example, the difference between "hit"/hɪt/ and "hat" /hæt/ is but one vowel sound. Sounds themselves are considered to have no meaning, and they are defined by the conventions of a language. English "hat" and Spanish "sombrero" both refer to an object covering the head but include different sounds. However, some sounds are very stable across languages.

We can observe astonishing examples of sounds bearing meaning in sound symbolism. But what does this mean? Let us look at a different example of a minimal pair than the two words hit and hat. Compare "zig"/zɪg/ and "zag"/zæg/. The difference in vowels is the same as in hit versus hat, but what about the difference in meaning? "Zigzag" paints a picture in our heads of a back-and-forth movement. In this example, /ɪ/ versus /æ/ evoke a feeling of an opposite direction of movement. The word zigzag is iconic; it creates a mapping between aspects of the acoustic signal and features of the action or visual image.

The most comprehensive study on sound symbolism that we are aware of is the one published by Blasi et al. (2016), who investigated almost 4,300 languages. These are about two-thirds of all existing languages! The authors used a list of 40 words from the Swadesh (1955) list, which encompasses a total of 100 concepts that are least likely to be borrowed from other languages. The Swadesh list was created to compare vocabularies cross-linguistically, aiming toward a better understanding of concept stability and change across language histories. Those concepts include body parts (e.g., eye, lips, breast), pronouns (e.g., I, we, you), and motion verbs (e.g., swim, walk), among others.

Blasi et al. (2016) analyzed the relationship between the occurrence or avoidance of sounds within those concepts

1 This paper is dedicated to Mary Wünsch.

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across languages. Several consistent associations between sounds and specific meanings were found. One example is an association between the vowel /i/ and the concept of "small," such as French "petite," or Maori "iti." In the following, we discuss possible reasons for further research on the sound-to-size mapping. Another example is the correlation of /m/ and /u/ with the concept of "breast." Both sounds engage the lips during articulation. For /u/, the lips are protruded and for /m/ they are closed. This use of lips has been discussed in terms of a direct relationship to sucking and breastfeeding in babies, therefore aligning with the meaning of breast. We later go into more detail and explore the evidence for sounds to create and, ultimately, bear meaning.

Cross-Modal Correspondence

Sounds can become meaningful when they are fused with other sensory information such as visual shape or touch. The product of this "fusion" is called a cross-modal correspondence. Everyday human life is full of cross-modal experiences. We perceive the world around us through all senses: smell, taste, touch, sight, and sound. Remember the example from the beginning, your favorite cake coming out of the oven. You may recollect the good smell in the air, the delicious taste, the texture in the mouth, and the mmm-sound. For sure, this cake looks good waiting for you on the table!

Sound symbolism is only one specific case of cross-modal correspondence. It is probably more common than we realize. For example, all diaper brand names in Japan and most in Germany include a bilabial consonant, a consonant that is produced using both lips, because we connect bilabial sounds with babies, who use their lips to suck milk and make the first sounds. A whole branch of marketing research deals with designing a perfect brand or product name according to what the product is, how it is used, and the target group. So, in supermarkets, our attention may be caught by a product name that is imposed on specific properties of the product and designed for a specific target group. The vowel /a/ can be correlated with dark beer rather than light beer, and women generally respond more favorably to products containing front vowels like /e/ or /i/ (Klink, 2000; 2009).

Examples of sound symbolism can also be found in fantasy names, such as Pokémon. And so, the strength or size of the Pokémon can be correlated with such things as the name length or the number of certain consonants. Here again, one sensory modality, such as the visual perception of size, might be reflected in the sound of its name.

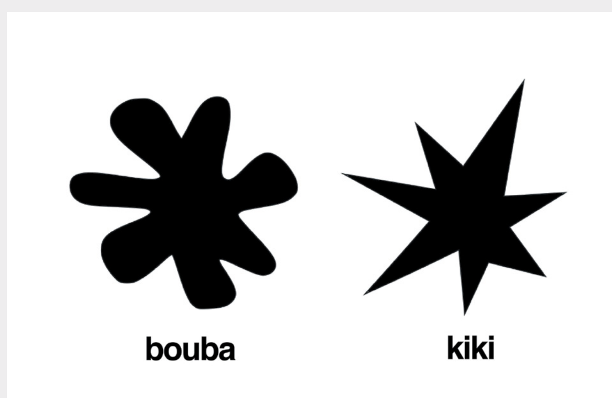
We now introduce a few examples of the fascinating world of cross-modal correspondences (for a review, see Spence, 2011). We picked some of the very popular ones and some that may be relatively less known. We do not wish to imply that every human will perceive these cross-modal correspondences in the same way. It must be borne in mind that sound-meaning relationships can also be specific for a particular language. However, here, we specifically rely on examples, which have been tested cross-linguistically. A large proportion of speakers across the globe would match selected sounds with other sensory properties. One reason for choosing these examples is that the role of sound symbolism in language evolution is discussed in **Cross-Modal Correspondence and Language Evolution**.

Sounds Map to Visual Shapes

One of the most popular cross-modal correspondences is the "bouba"/"kiki" effect, originally known as "baluba"/"takete" (Köhler, 1947). It has been repeatedly shown that when people are asked to match the pseudowords bouba and kiki to a visual shape, most of them will use bouba for the round shape and kiki for the spiky shape (**Figure 1**).

When asked to draw the fantasy characters called bouba or kiki, the artist may end up with characters as shown in **Figure 2**. Those also exhibit rounder shapes for the

Figure 1. *The visual shapes representing a round shape correlated with bouba and an angular shape correlated with kiki. Adapted from Ćwiek et al. (2022), under CC BY 4.0 license.*



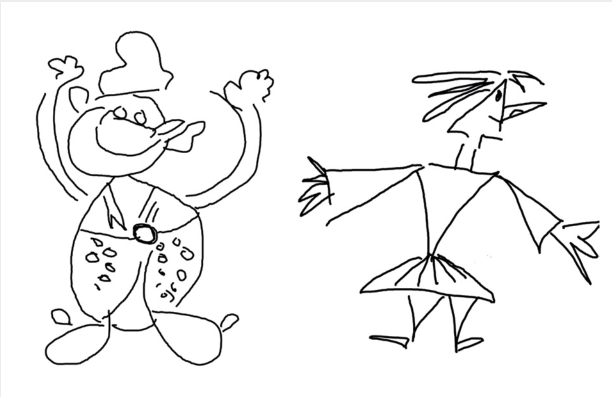


Figure 2. *Drawings of fantasy characters called bouba (**left**) and kiki (**right**). Courtesy of painter Mary Wünsch.*

bouba character and spikier shapes for the kiki character. Interestingly, even the sound of drawing a round versus a spiky shape on paper can be reliably characterized and assigned to the correct bouba and kiki figure, respectively (Margiotoudi and Pulvermüller, 2020).

The effect is a robust cross-linguistic phenomenon (Ćwiek et al., 2022), which has also been shown in infants and children. There are different opinions as to why the sound-to-shape matching takes place. Some say the effect originates from articulation. In bouba, the /uː/ is a rounded sound involving lip protrusion and the /b/ is produced with the lips. In kiki, the /k/ causes the tongue to move up and down, releasing into the vowel. So, the articulatory motions themselves seem rounder or smoother in bouba and more abrupt in kiki.

Others have argued that the acoustic characteristics of the pseudowords match the visual shapes (Ćwiek et al., 2022). During /k/, the fundamental frequency is absent, leading to a period of silence followed by high-intensity, noisy spectral energy. The fundamental frequency and formants only begin at /i/. In contrast, bouba is produced with a continuous fundamental frequency and overall lower spectral energy, so that the changes are less extreme.

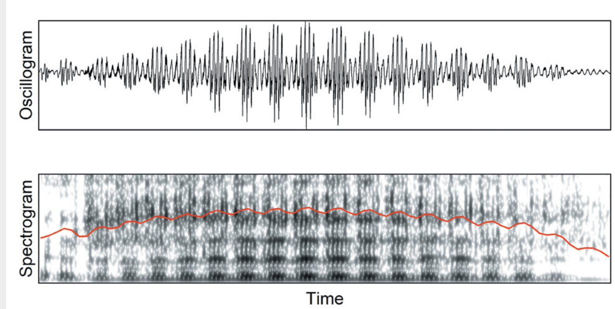
A potential bias with orthography (a system of writing conventions) has also been discussed in the literature. Some researchers have wondered whether the sound-symbolic mapping is not a cross-modal correspondence between sound and shape but rather a shape-to-shape matching between the orthographic shape of letters to the depicted images. The Roman letters <b>, <o>, and <a> are obviously round, whereas <k> and <i> are spiky. However, people around the globe, using different alphabets, match shape and sound in a similar way relatively independent of their orthography (Ćwiek et al., 2022).

For example, in Georgian, the orthographic representations of bouba = ბუბა and kiki = კიკი both look round. Nevertheless, Georgian speakers match the sound of bouba and kiki to the respective round and angular shapes as reliably as speakers of other languages and orthographic systems. If orthography can evoke a bias, this bias is rather weak, whereas sound-to-shape mapping is a robust phenomenon.

Sounds Can Map to Texture

Cross-modal correspondences between sound and touch are less known, but there is reason to believe that these correspondences are deeply connected in evolution. Touch is crucial in sucking, swallowing, mastication, and speech production. The major articulator, the tongue, does not move in free space but is rather in close contact with different vocal tract boundaries. Putting hands on the front of the neck, one can feel the resonances caused by the vocal fold vibrations in sounds that include phonation. There has even been a method called "Tadoma" for deaf-blind individuals that allows them to perceive speech via touching the cheeks and neck of their interlocutor (Rosenblum, 2019). Resonances can also appear on the skin of the neck while vibrating the uvula in a uvular-/ʀ/, similar to when a person is gargling. **Figure 3** shows an acoustic signal

Figure 3. *Acoustics of a tongue tip trilled r-sound. **Top:** an oscillogram. **Bottom:** a spectrogram with the amplitude envelope superimposed (**red line**).*



of a tongue tip /r/-trill, one variety of an r-sound that is common in many languages.

A recent comprehensive study by Winter et al. (2022) has demonstrated compelling evidence for a close link between trilled /r/ and rough surface textures. A rough texture can correspond to an oscillating amplitude envelope (**Figure 3,** *bottom, red line*), but to our knowledge, this idea has not yet been tested explicitly.

Touch and sound are not only linked during speech production but are also connected during object manipulation. Moving the hands along plain paper or the bark of an old tree causes natural sounds that depend on the surface and structure of these two objects. Hence, sound and touch are related, reflecting the texture of the physical world around us.

Winter et al. (2022) found out that words describing rough surfaces (e.g., coarse, barbed, jagged), in comparison to smooth ones (e.g., smooth, oily, slick), have an overrepresentation of r-sounds. To further substantiate their findings on the cross-modal correspondence in sound and touch, they looked at Hungarian, a language with different family roots from English. In Hungarian, similar to English, r-sounds occurred much more frequently in words describing rough textures.

In addition, Winter et al. (2022) compared the antonym pairs *rough* versus *smooth* across 179 languages with a trilled r-sound in their sound inventory and across further 153 languages with a non-trilled r-sound (for different variations of r-sounds, see youtu.be/K9eN2B7Wj68). Only languages with a trilled r-sound, such as Finnish and Indonesian, show a higher probability of /r/ in a word for rough compared with smooth. This shows the resemblance of touch being mapped onto the articulation and acoustics. These findings are an initial attempt to unravel correspondences between touch and sound. If we think about cross-modal correspondences during ingestion as in our initial example, it would not be surprising to find links between sound, touch, and taste as well. We are looking forward to future discoveries along such lines.

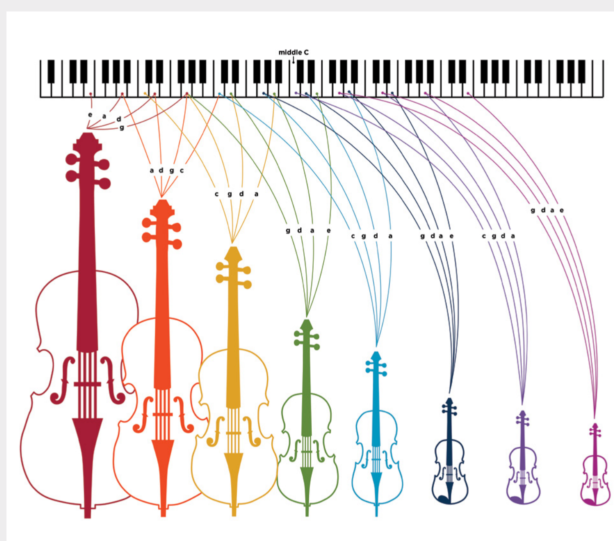
Sounds Can Map to Visual Size

The relationship between certain sounds and size is perhaps the most well-known example of sound symbolism. It turns out that specific speech sounds express the notion of size. The most famous example might be the one between the two vowels /a/ and /i/. In many languages, the physical size dimension is conveyed by those opposing vowels (e.g., Winter and Perlman, 2021). Whereas /a/ is an open vowel, /i/ is a closed one. The radical difference in their articulation evokes the contrast. When we say "teeny tiny," we might even squinch our eyes and lips to make the sensation even more closed and smaller. The opposite is the openness of something "large" or "huge," with a dropped jaw and low voice.

And truly, the reason behind this difference may be as simple as the fundamental frequency of the voice and certain spectral characteristics. Imagine two dogs, a 50-kg (110-lb) German shepherd and a 2.5-kg (5.5-lb) chihuahua. How do you expect their barking to sound? Certainly, even without expertise in acoustics but simply some basic life experience, you know that a 50-kg dog would have a lower pitch bark than a 2.5-kg dog. This example from the animal kingdom extends to other realms.

Let us look at bowed string instruments of various sizes in **Figure 4**. This image stems from the Spring 2020 issue of *Acoustics Today*, where Carleen Hutchins' creation of a violin octet with different resonances, but tonally matched instruments, was featured (Whitney, 2020). You

Figure 4. *Bowed string instruments of various sizes and tuned across a piano range. See text for details. From Whitney (2020), with permission of the New Violin Family Association.*



can see the tuning of those instruments across a piano range. Those instruments have different physical properties, from the resonant body, through the length of the neck, to the thickness of the strings. All of them have four strings, but those strings are tuned very differently from one another. For example, we would not expect any of the strings of a large instrument, like a double bass, to be tuned to E5, which is usually the tuning of the highest string on the regular-sized violin. The larger the instrument, the lower it might sound and vice versa.

The correspondence between sound and visual size might stem from such physical properties. The theory explaining this connection in humans and other animals is called the "frequency code" and was proposed by Ohala (1994). Among other examples, Ohala stated that lower frequencies typically originate from larger sources and higher frequencies from smaller sources. This drives our expectations and can, in turn, be mapped onto more abstract relationships that we can create with the tone of voice, such as the fundamental frequency. Thus, he says that a lower fundamental frequency expresses dominance and a higher fundamental frequency submissiveness. In the end, being larger in the animal kingdom might make an animal threatening and more attractive for mating.

These basic correspondences can move into broader sociocultural uses. Using a high fundamental frequency with exaggerated peaks is typical for child-directed speech. And the reason for that might be that it seems less threatening and more playful to children. As an opposite example, we might look at the so-called "creaky voice," as an extreme case of vocal fry (sounding like an aperiodic low voice; see youtu.be/4L7-9N1xQZA) caused by shortening the vocal folds and lowering the fundamental frequency, occurring mostly in young women. It started gaining popularity in the 1960s and was later covered in pop culture (see Frank and Moon Zappa's song "Valley Girl," at youtu.be/Qb21lsCQ3EM). Originally, the strategy of lowering the fundamental frequency should evoke the image of competence; however, the actual perception of this phenomenon is mixed. Therefore, we have to bear in mind that some abstract social meanings such as competence or politeness seem more complicated and may interfere with the use of the frequency code (Winter et al., 2021). Nevertheless, we might still find support for it in our own voice use in different contexts.

Cross-Modal Correspondence and Language Evolution

Meaningful cross-modal correspondence between sound and size is not only something that humans perceive and use. It is a crucial mechanism in the animal kingdom and its relevance has at least the two following reasons. First, animals sense danger using a variety of perceptual signals, with hearing being a particularly powerful sense.

Second, some animals use the sound-to-size correspondence as a deceptive strategy to their evolutionary advantage (e.g., Bee et al., 2000). A signal can be deceptive if it does not correspond to the actual body size of the vocalizing animal but implies a bigger animal. In that case, it can be a potential threat to the receiver and may increase the chance of survival and mating success. To what extent such a signal is intentional or not is not the main concern of this paper. The use of voice for size estimation is perhaps best visible in the behavior of various deer species (e.g., Reby et al., 2005). The question here is about perception and adaptation. When confronted with roars that suggest a large-sized caller, male red deer respond more frequently and extend their vocal tract due to laryngeal lowering that changes their resonant frequencies (Reby et al., 2005). Studies also show that larger deer have lower frequencies and through that, indirectly, a higher mating success (Vannoni and McElligott, 2008).

The use of sound to deceive and communicate an exaggerated size has been shown in a variety of species so far (e.g., Bee et al., 2000). Some examples include squirrels, birds, and frogs. The deception can function across and within species. For example, juvenile squirrels imitate the voice of their parents to drive away predators (Matrosova et al., 2007). Birds may strategically use vocalizations of their predators to fool fellow birds and enjoy an uninterrupted feast on flies themselves (Munn, 1986). Some frog species lower their fundamental frequency to seem larger in the eyes of other frogs and protect their territory (Bee et al., 2000).

Research on Primates: Empirical Research Is Mostly Unimodal

Although discoveries about sound-sized linkages in animal communication promised to be very fruitful, most studies on primates have been unimodal. In the early stages of research in this field, many findings evolved around the gesture-first theory (Hewes, 1973).

Later, alternative approaches gained attention. From those, we learn that western lowland gorillas, *Gorilla gorilla gorilla*, have impressive control over their breathing behavior (Perlman, 2017). Perlman reported that Koko, a female gorilla (for information and videos, see bit.ly/3HKY47C), could drink through a straw and used different types of breath signals to communicate her attitude. She blew gently onto the face of a person she was fond of and harshly onto someone she did not wish to talk to. Koko not only employed breathing signals but also vocal signals; both were frequently accompanied by gestures (Perlman and Clark, 2015). Works like these might introduce us to the onset of volitional control over vocal behavior. However, it does not stop there. We have known for a few decades that primates, and here we specifically refer to free-ranging East African vervet monkeys, *Chlorocebus pygerythrus*, have different alarm calls for different predators. A call for an eagle is distinct from a call for a leopard, among other threats and predators (Seyfarth et al., 1980). In the end, hiding from an eagle is different than hiding from a leopard.

Even more compelling, however, is the evidence from human-fostered individuals or groups. Kanzi might be the best-known among his species (Savage-Rumbaugh et al., 1986). This male bonobo, *Pan paniscus*, was taught to communicate with so-called lexigrams, a set of symbols conveying a certain meaning (Savage-Rumbaugh et al., 1986). Less known, although not less impressive, was his ability to communicate using vocalizations. Kanzi not only used specific vocalizations in different semantic contexts, but he also modified those vocalizations (Hopkins and Savage-Rumbaugh, 1991). His behavior was similar to modulations such as talking with a higher fundamental frequency to express child-directed speech. Finally, it has previously been shown that both orangutans (*Pongo*) and chimpanzees (*Pan troglodytes*) are able to develop novel vocalizations to capture the attention of their caretakers (Lameira et al., 2016). Such vocalizations are structurally more like human speech than typical primate vocalizations. All in all, this evidence shows that great apes do not only rely on gestures. They very much strategically use vocal signals, too.

According to Slocombe et al. (2011), theoretical approaches in favor of gestures or vocalizations might be biased by empirical work. In a meta-analysis of empirical work carried out between 1960 and 2008, only 5% of the 553 studies on primates analyzed vocalizations and gestures together. In the rest of the studies, researchers focused on one modality only, supporting the respective theoretical view. That means researchers following the gesture-first theory supported their claims with empirical data from gestures but did not challenge it with vocalizations. The same is true for theories focusing on vocalizations, which used empirical data on vocalizations without confronting it directly with gesture data.

Another methodological issue is that approximately 90% of the empirical evidence comes from animals in captive environments with all its consequences on, for example, social behavior, motion, and diet. Furthermore, the living environment of the animals is tightly coupled to the objective of the study. For animals recorded in the wild, researchers focus on vocalizations rather than gestures, which is very likely due to methodological challenges such as the unpredictability of gestures, moving animals, animals interacting within a larger social group, and changes in the camera perspectives. On the other hand, gesture research has often been carried out in captive environments such as zoos. These methodological differences led Slocombe et al. (2011) to a call for more multimodal research to substantiate the theoretical approaches.

Ten years later, Liebal et al. (2022) conducted a similar meta-analysis across 294 studies published between 2011 and 2020. Although certain research gaps have been closed, Liebal and colleagues reported a significant decrease; only 2% of the studies were multimodal.

Pros and Cons for the Role of Vocalizations in Language Evolution

The unimodal perspective on the emergence of communication has spread across the discipline and affected the view on human communication as well. With hand gestures, one can, for example, indexically refer to spatial locations, iconically imitate actions, and depict shapes and sizes of objects. One argument for gestures as the onset of communication is that it was possible to teach some captive apes American Sign Language but not spoken communication.

Another frequently noted fact is that gestures facilitate communication with infants and babies who yet cannot speak. Babies who were taught to use a simplified visual communication system can communicate their

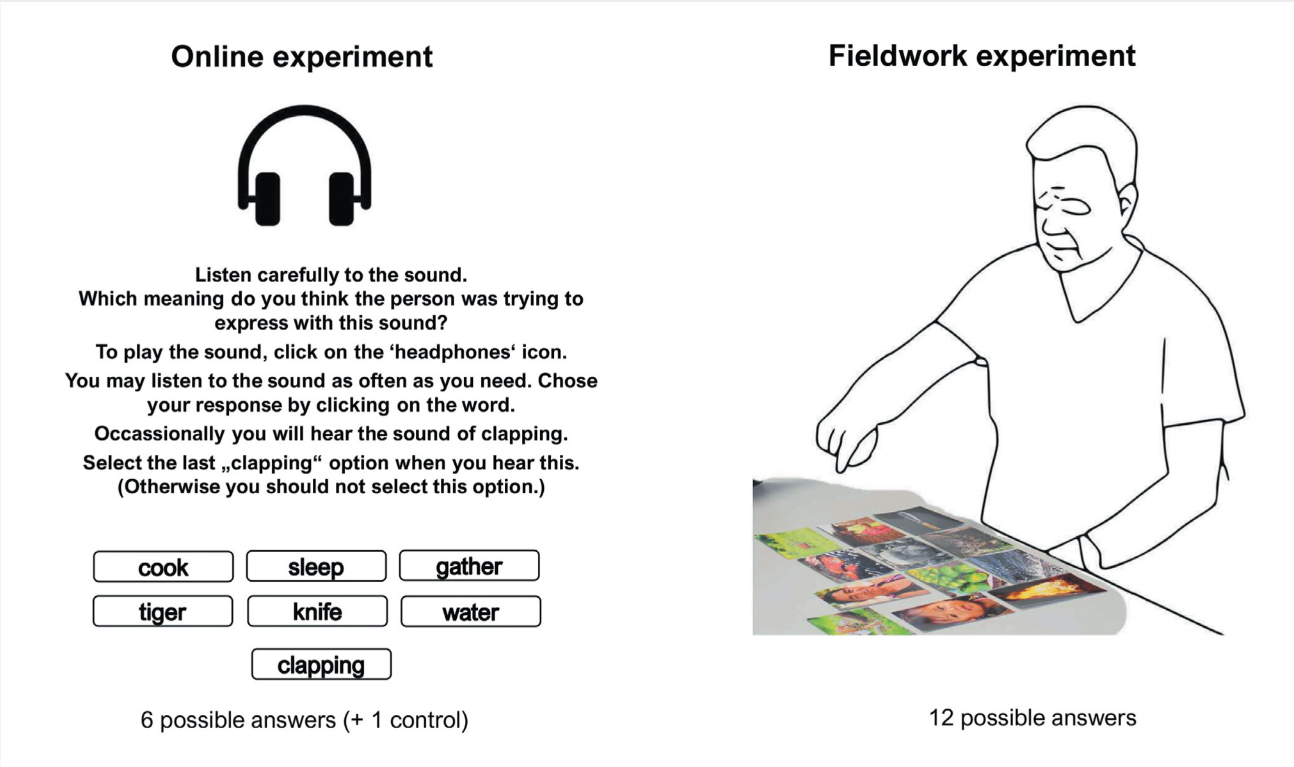


Figure 5. *An overview of the experimental setup.* ***Left:*** *online version of the study.* ***Right:*** *setup in the field experiment. Taken from Ćwiek et al. (2021), under CC BY 4.0 license.*

needs much earlier than would be possible with speech (Barnes, 2010).

A major problem with the assumption that human communication has its origin exclusively in gestures, however, is that it does not explain at *what stage* and *why* a switch from the visual modality toward the auditory modality should have taken place. Furthermore, it has long been assumed that vocalizations might be less depictive than gestures for the creation of novel form-meaning relations.

However, a recent investigation has shown that vocalizations have a much larger iconic potential than previously assumed and can, thus, ground meaning (Ćwiek et al., 2021). In two experiments, an online study and a field experiment, listeners from all over the world heard acoustic signals that were created without using conventional language. These signals expressed a variety of basic concepts like *fire, water, man, woman, snake, hunt, eat, big,* or *many* that might have played a role in the communication of our ancestors (see the Open Science Framework repository for examples at osf.io/4na58). Almost 1,000 participants from 28 languages and 12 language families listened to the vocalizations and selected what they felt was the intended meaning from among different options.

Figure 5 presents how the procedures looked. In the online study, listeners chose 1 from among 6 potential concepts, whereas in the field experiment, they chose the meaning from among 12 pictures. This was done to make the setup accessible to people from different educational backgrounds.

Against previous assumptions, the results of the two experiments showed that participants around the globe were able to comprehend the meaning of these concepts far above the chance level. Thus, the acoustic signal alone has the potential for humans to infer meaning without using language. Still, this does not imply that communication necessarily started only with vocalizations.

The emerging conclusion is that the interplay of gestures and vocalizations might have been crucial at the dawn of communication. It is an advantage to use both because they have different affordances. On one hand, those affordances are situational. Vocal calls are useful to reach a distant receiver, and visual communication might be preferred in close communication or even demanded when we do not wish to attract the attention of others. On the other hand, different affordances relate to the expression of different sensory dimensions. Something visual, such as the shape of an object, is easier to convey using gestures, whereas something auditory, like the tick tock of a clock, may be easier expressed with vocalizations. The connection between the modalities, exposed by cross-modal correspondences, only proves that they are both vital and intertwined. Although it has been pointed out that for human communication it is multimodal at the core, this may also be true for other primates when communicating.

Concluding Remarks

Sounds can become meaningful when they are fused with other sensory information. This property was important to get language off the ground and goes against the traditional assumption in phonology that sounds are only described as meaning-distinguishing units. We provide examples for robust cross-modal correspondences of sound-to-vision and sound-to-touch mappings. Cross-modal correspondences are part of our daily life. They can occur in child-directed speech, in product names, and in fictional characters of cartoons or movies. Sound-to-size correspondence is also meaningful in the animal kingdom. Perceiving the size of a predator in the vocal call of its voice (sound-to-size mapping) can become a matter of survival. However, interdisciplinary work might be necessary to move comparative studies on humans and primates forward because most empirical work on animals focuses on either auditory vocalization or visual gestures. Studies in the wild may face all kinds of methodological challenges. Joint effort by scientists working on open databases for acoustics of animal communication, tools for signal processing, machine learning, optical flow, and video analyses will be necessary for future discoveries.

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Acoustics in Music Archaeology: Re-Sounding the Marsoulas Conch and Its Cave

Miriam A. Kolar, Carole Fritz, and Gilles Tosello

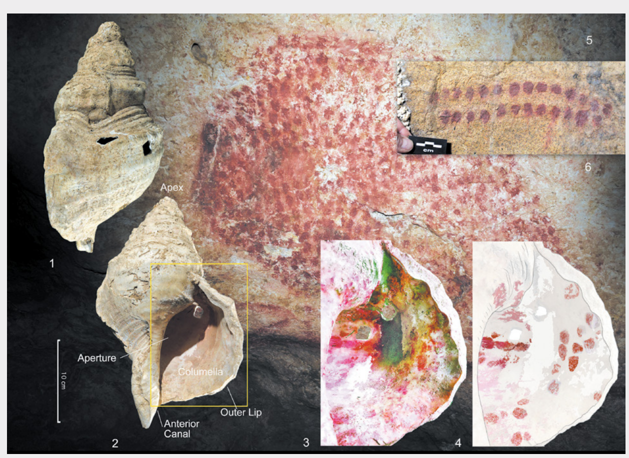
What can be learned from the sounding of a conch shell after it has been silent for 18,000 years? During the last ice age in what is now southern France, a person or people from the Magdalenian period (see bit.ly/3uCjlMc) procured a giant conch (*Charonia lampas*) (**Figure 1**) from the Atlantic Ocean and transported it more than 240 km (150 miles) to a narrow cave in the Pyrenean foothills (Haute-Garonne, France). This elaborately decorated limestone cave, known as Marsoulas (**Figure 2**), extends from its small opening like a long narrow corridor with a triangular cross section, proportions distinct from the voluminous caves typically known for Upper Paleolithic art.

The large seashell, which functions as a natural horn, bears evidence of several modifications by humans (Fritz et al., 2021). Other finds in the cave include hematite rocks and tools that may have been used to produce the red pigment adorning both the cave and the interior of the seashell. This is a rare archaeological assemblage of materials that directly link expressive visual culture with human soundmaking in the Upper Paleolithic.

Music Archaeology's Premise: Instruments, People, and Places Make Context

Music archaeology grapples with the challenge of recovering clues about purposeful soundmaking by humans in contexts distinct from those today. Thousands of years before written language, although at the same time as graphical artworks such as wall paintings, engravings, and sculptures, humans made music as evinced by the discovery of 35,000-year-old bone flutes discovered in caves of the Swabian Jura from the Aurignacian period (see bit.ly/3ITVDQC). Musical instruments are considered the most specific form of archaeological evidence for humans' nonverbal sonic expression. Therefore, musical acoustics research can aid in evaluating sounds that archaeologically evidenced instruments could make. However, explorations of instrument acoustics alone cannot reconstruct ancient music; the places where music was made are indicators about many aspects of musical behaviors as well as experiences that can be related to spatial acoustics. Instruments, people,

Figure 1. *Archaeologically excavated marine shell of* Charonia lampas *from the Marsoulas Cave (Haute-Garonne, France).* ***1*** *(**Top left**): side view.* ***2*** *(**Bottom left**): front view with the anatomical areas indicated.* ***3*** *(**Bottom center**): vestiges of red pigment (image enhanced with Dstretch software).* ***4*** *(**Bottom right**): tracing of the red dots and lines that are visible on the enhanced photo. Very similar red dots, produced with the fingertips, are present on the walls of the Marsoulas Cave.* ***5*** *(**Top center**): set of red dots forming a bison silhouette (length, 1.10 m).* ***6*** *(**Top right**): geometric sign formed by a double line of dots (shown with a centimeter scale). Photos 1, 2, 3, 5, and 6 from C. Fritz; drawing 4 from G. Tosello.* ***Figure 1*** *previously published in Fritz et al. (2021, Figure 1).*



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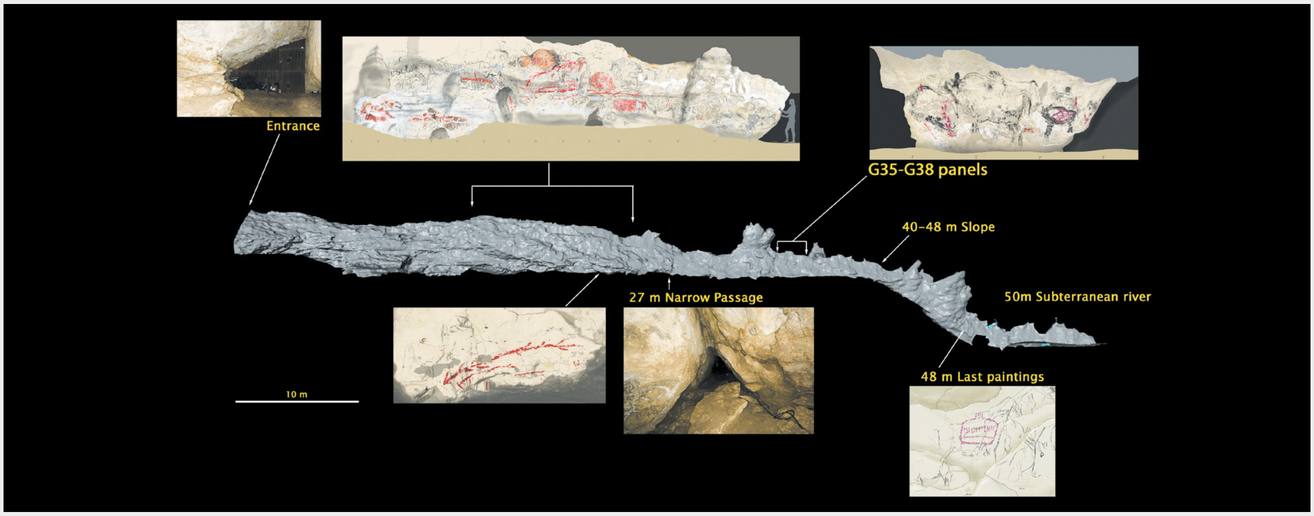


Figure 2. *Three-dimensional (3D) profile of the Marsoulas Cave from the entrance to the end (**gray area**). The decorated sections known as panels G35-G38 are presented as examples of the visual reconstructive methodology (Fritz et al., 2016). Note the cave's triangular cross-section (**top left**), and the location of its central bison panel, the site of preliminary acoustical measurements. **Figure 2** previously published in Fritz et al. (2016, Figure 1).*

and places together create the musical context explored in archaeological interpretations.

Archaeology must produce inferences regarding past human lives via remnant materials (see tinyurl.com/2a6te2m2), whereas acoustical science provides a physical basis for exploring those materials in terms of their production and transformation of sound. Acoustics and auditory science can be joined with archaeological methods to reconstruct aspects of sonic communication by humans in past settings (Kolar, 2018). Although musical instrument acoustics have been applied in many archaeological studies, less attention has been given to spatial acoustics of archaeological sites that are not known as musical or theatrical venues, such as the decorated cave where the Marsoulas conch was recovered in 1931. At that point, the conch was catalogued as a drinking vessel or ritual cup.

As an example of the utility of acoustical methods in exploring an archaeological context with musical evidence, this article highlights the study of the Marsoulas conch horn and its cave. The antiquity of Upper Paleolithic sites such as the Marsoulas cave, many of which are noted for their wall art, requires the broadest definition of music as nonverbal soundmaking by humans. The comparison of the visual artworks in this cave with techniques used to decorate the sound-producing conch that was found inside the cave demonstrate a symbolical connection between the instrument and place. In both the wall art and the shell modifications, there is pattern replication, evidence of compositional strategies, and exploration of forms from nature. To decorate the cave and the conch, humans were using visual expressive techniques that parallel those employed in historical and present-day art making; whether Paleolithic people also extended such media manipulation strategies to sonic expression is unknowable, yet is a topic to be approached through a cognitive archaeological framework. However, there is much information about past music making that can be explored through acoustical science, which provides the tools for evaluating instrument performance features, contextual manipulation, and physical interactions between sound producers and performance settings.

Music Archaeology's Acoustical Expansion

A field once focused on the identification of sound-producing instruments from archaeological materials (Eichmann, 2018), music archaeology now employs acoustics, following a larger trend in archaeology to integrate scientific methods from fields appropriate to the materials or topics being investigated (Johnson, 2020). Musical acoustics has gained recognition as the archaeometrical approach to characterizing ancient and historical sound-producing instruments, such as techniques employed to reconstruct the Deskford carnyx, a 2,000-year-old

Celtic brass sculpture as well as a lip-reed aerophone (see tinyurl.com/2adkpap3) (Campbell and Kenny, 2012).

Beyond musical instrument acoustics, a variety of acoustical research areas are being pursued in music archaeology. Spatial and architectural acoustical methods enable the exploration of interconnections between instruments and sites of their excavation or documented use, such as in the musical instrument-supported acoustical survey of the central platform and plaza at the Inca administrative city Huánco Pampa (see rogeratwood.com/article/inca-power-politics) (Kolar et al., 2018). Along with a standard spatial acoustics test signal, that study employed human-produced sounds with archaeologically appropriate instruments (a conch shell horn, a whistle, and human voice) repeated to account for performance variations. Although necessary in connecting physical acoustics with their human perceptual implications, the auditory sciences are infrequently applied, with notable exceptions such as a recent multimodal study of flintknapping (Smith, 2020) in which acoustic feedback was considered a feature in the crafting of stone tools.

Studies of performance mechanics further refine archaeological interpretations about sound-producing instruments. Much attention has been given to the contentious topic of whether certain bones found in Paleolithic archaeological contexts may have been flutes; biologist and flautist Jelle Atema has conducted detailed experiments in both instrument production and performance to recommend nuanced criteria for the evaluation of proposed sound-producing instruments (Atema, 2014). When performance explorations are connected anthropologically, as in the archaeo-ethnomusicological study of Andean music by Olsen (2002), reconstructive hypotheses can be evaluated in terms of known practices across cultures. Musical acoustics methods enable the reevaluation of archaeological classifications previously made without physical explorations to revise functional hypotheses, as in the study of sucked trumpets across prehistoric Europe and North America (Rainio, 2016). Thus, it becomes clear that acoustics and auditory science offer a range of theoretical and experimental tools to inform music archaeology's expanding terrain (Stöckli and Howell, 2020).

Whereas research in musical instrument acoustics (see newt.phys.unsw.edu.au/music) aids in the mechanical evaluation and description of archaeological objects that can produce sound (Wolfe, 2018; Campbell, 2021), research on spatial acoustics is equally important in characterizing the settings for past music making and musical perception. Architecture can be sound enhancing, such as the temple of Kukulkán (ca 1050-1300 CE) at Chichén Itzá (see tinyurl.com/2s3pynke) (Lubman, 1998). Buildings and structures can also be sound producing, such as the pre-Hispanic "sprung dance floor" in the site of Viejo Sangayaico (ca 1000-1615 CE) in southeastern Perú (Lane, In Press). Reconstructions of place-based musical practices present opportunities to study sound-makers in context, such as research on conch shell horns at Chaco Canyon (see whc.unesco.org/en/list/353) in the North American southwest (Loose, 2012) and in recent aerophone reconstructions from the first-millennium metropolis of Teotihuacan near Mexico City (see whc.unesco.org/en/list/414) (Both, 2021).

Acoustic interactions between sound-producing instruments and both built and natural structures provide clues to identify and characterize past human musical activities and experiences of particular places. For example, the study of two early-twentieth century carillons in Toronto, Ontario, Canada (see acousticstoday.org/heritage-carillons) explored "the instrument and its context...holistically, more accurately reflecting the musical sensitivity of a carillonist" by "spectral analysis of audio samples of each bell at different musical dynamic levels [that] enabled the analysis of the acoustic qualities of the bells and the mechanical action of the instruments" (Orr, 2021, p. 1). Orr's in situ research detailed the instrument-building interactions that influence performance practices as well as audience perceptions. The cross-comparison of spatial and instrument acoustics can suggest ritual functions, as in the study of conch shell horns in the enigmatic first millennium BCE stone architecture of Chavín de Huántar, Perú (see whc.unesco.org/en/list/330), where parallel ducts filter and project the fundamental tones of these instruments between a hidden carved monolith and a countersunk plaza that is decorated with relief carvings of conch shell horn performers (see tinyurl.com/yacxey3d) (Kolar et al., 2012).

Acoustical Music Archaeology: Investigating the Marsoulas Conch and Its Cave

Studying how the Marsoulas conch sounds and the ways its sound can be transformed within the painted cave where it was discovered reveals physical parameters about ancient music in a site that was previously only renowned for its elaborate visual artwork. In the cave, around 500 motifs, including geometric markings and more than 340 paintings of animal and human figures both engraved and painted in red (hematite) and black (charcoal), cover the short walls of a limestone corridor long ago carved out by water. "The art of Marsoulas is of profound stylistic originality with few equivalents in the region from the same period" including naturalistic horses, bison, and other horned animals (Fritz et al., 2016).

Marsoulas cave's small cross section is a physical constraint for both visual and musical expressive activities within the cave that guides hypotheses about possible social configurations, limiting where and how many people could have engaged with the art and acoustics. For example, it could be practical to project the sound of the powerful conch shell along the median axis of 100 meters (328 feet), yet even a few people within the cave could dampen the sound, as demonstrated in performance tests.

The first step in a music archaeological investigation is questioning the musical premise. Only recently was the Marsoulas conch identified as a possible sound-producing instrument, nearly a century after its archaeological recovery. Initial research on the seashell documented its physical and acoustical features and presented physical evidence for its modification and use as a tool for sonic expression (Fritz et al., 2021). The investigators' approach to the Marsoulas conch included characterizing human modifications to the shell that include strike marks around its lip, an opened spire, and a mysterious circular perforation that may have pierced the external spire and extends through two turns of the horn inside (Fritz et al., 2021). Performance acoustics were explored at the Maison des Sciences de l'Homme in Toulouse, France (MSHS-T) where a musicologist and horn player performed the seashell as a lip-valve "natural horn." The performance of the artifact shell produced sounding tones of fundamental frequencies at 256, 265, and 285 Hz, with harmonics typical of such instruments having a conical bore (interior cavity) (Wolfe, 2020).

To corroborate their experimental verification of the seashell as a sound-producing instrument, the investigators sought ethnographical analogies for similarly modified shells, which sometimes have external mouthpiece modifications and additions, as shown in **Figure 3**, *right panel*, 6-10.

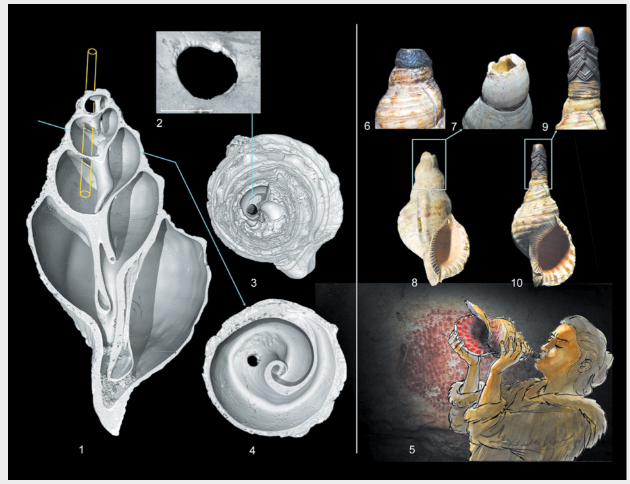


Figure 3. *The* Charonia *wind instrument.* ***Left panel: 1 (left)****: sagittal section of the 3D model of the shell that makes it possible to visualize the hole drilled at the level of the sixth spire.* ***2 (Top right)****: detail of the circular perforation drilled from the apex. The streaks on the edge are due to a skidding tool.* ***3 (Middle right)****: top view of the 3D model showing the perforation.* ***4 (Bottom right)****: 3D cross section at the level of the seventh spire.* ***5****: (****Bottom right****): the conch of Marsoulas in its Magdalenian context (hypothetical restitution).* ***6****: (****Top left****): conch from Southeast Asia, the mouth of which is covered with a black coating, intended to protect the lips of the blower.* ***7*** *and* ***8****: Conch from Syria (****left middle****) and detail of its chipped mouth (****top middle****), close to that of Marsoulas.* ***9*** *and* ***10****: Conch from New Zealand (****middle right****) and its mouthpiece made of a decorated bone tube (****top right****). 3D model captures 1 to 4 from C. Fritz; drawing 5 from G. Tosello; photos 6 to 10 from E. Kasarhérou, Musée du Quai Branly-Jacques Chirac, Paris, France.* ***Figure 3*** *previously published in Fritz et al. (2021, Figure 3).*

Despite the Marsoulas conch's compliance in tonal sound production, its researcher-performer noted its jagged and uncomfortable mouthpiece, which bears evidence of prior application of "a thin layer of a brownish colored material preserved on the outside and inside of the apex" (Fritz et al., 2021, p. 1) that is hypothesized as a substance used either to smooth the mouthpiece or to affix an attachment. Curiously, even with its pointy spire removed as required to create a natural mouthpiece, the Marsoulas conch was perforated by a 1-centimeter-diameter circular hole bored through two turns of its coiled conical interior, enabling the insertion of a narrow tube as illustrated in **Figure 3**. Although these aligned circular perforations can function to stabilize an inserted tube, their diameter is much smaller than would be appropriate for an externally affixed mouthpiece, a consideration not explored in the initial study.

Due to the age and fragility of the Marsoulas conch, two resin replicas were commissioned, including the application of pigments to replicate those inside the archaeological shell. In September 2021, we compared the Marsoulas conch with its resin replicas in the Museum of Toulouse. The two resin replica horns produced tones with central frequencies comparable to those of the ancient seashell, verifying their suitability as experimental proxies. We then traveled to several caves in southern France for performance tests using one of the replica conch horns in associated archaeological settings, including a brief visit to the Marsoulas Cave where we made spatial acoustical impulse-response measurements and documented performance tests with the replica instrument. The long and narrow cave has been laser scanned and its extensive artworks investigated using customized image-processing techniques that allow production analyses and multimedia reconstructions (Fritz and Tosello, 2010), as shown in **Figure 2** (Fritz et al., 2016).

The reunion of the Marsoulas conch, in the form of its functionally equal resin replica within its excavation context, the Marsoulas Cave, enabled observations about musical plausibilities in a site of the shell horn's likely ancient sounding. Performance experiments can identify contextual sound effects, and they enable the description of site acoustical features that can be measured and expressed according to standard procedures and metrics. Both outside and inside Marsoulas cave, the sounding tone of the replica conch horn was measured from 258 to 260 Hz, within expected range of variation around the 256-Hz fundamental frequency documented in the shell horn's acoustical study (Fritz et al., 2021). We first performed the replica horn on the edge of the ravine outside the opening of the cave into the adjacent valley below (**Figure 4**), from where we heard and recorded converging echoes that prolonged the instrument's sounding tone for almost four seconds. In performance tests inside the cave, we documented frequencies produced using the downward pitch-bending technique in which the player's hand is partially inserted into the shell lip, or musical instrument bell, effectively lengthening its bore (Campbell et al., 2021). With the replica conch, the performer could "bend the tone down" to 234 Hz, extending the shell horn's frequency range. Although to observers, sounds from the replica conch horn did seem to "fill the cave," its performance did not notably excite spatial acoustical modes as we have observed in archaeoacoustics research with shell horns in architectural settings of similar dimensions, such as the stone galleries of Chavín de Huántar, Perú (see tinyurl.com/yckmef63) (Kolar, 2019).

Figure 5. *Experimental setup for acoustical impulse-response measurements in the central section of the Marsoulas Cave, adjacent to its iconic, red-dotted bison image (**right**). A portable omnidirectional loudspeaker and spatial audio recorder were used in this fieldwork conducted by Kolar, Nerness and Valentin in September 2021. Photo by Barbara Nerness.*

Figure 4. *A music archaeology experimental study just outside the Marsoulas Cave using a 3D-printed and hand-painted replica of the Marsoulas conch. Performed here by auralization researcher Romain Michon. Photo by Barbara Nerness.*

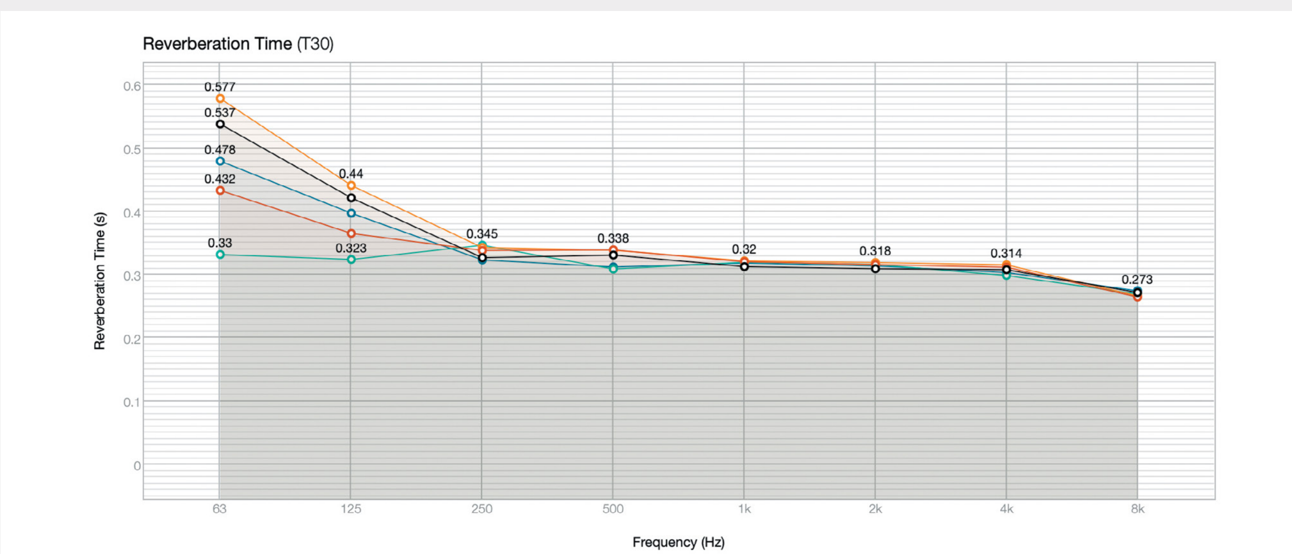
Characterization of how the Marsoulas Cave modifies sounds produced within was done using portable audio electronics (**Figure 5**) to make spatial impulse-response measurements. This is the standard procedure for room acoustics, where a known signal is produced from a source and recorded by microphone receivers for analysis. The sound source and receiver were located at approximate human head heights in various positions within the central section of the cave. Due to prior excavations and the presence of a few metal support structures, there cannot be perfect correspondence between the extant cave interior and its conditions during Magdalenian times. However, the overall dimensions and cross-sectional geometries of the cave have not been modified (as evinced by the intact paintings); therefore, measured acoustical parameters and noted structural features would have been similar during the Upper Paleolithic.

Impulse-response measurements are the standard technique for documenting how an enclosed space reflects and absorbs acoustic energy throughout the frequency spectrum of human audition and bodily sensing. One of the most common acoustical metrics for enclosed spaces that has strong perceptual implications is reverberation time. In the Marsoulas Cave, an analysis of spatial impulse responses collected in locations near the wall art indicate short reverberation times across most of the range of human hearing, around 300 milliseconds for octave bands centered at 250 Hz (near the Marsoulas conch's sounding tone) and above. The standard RT30 metric for reverberation time (**Figure 6**) shows an increase in the prolongation of sound with decreasing frequency, reaching about a half-second duration in the 63-Hz centered band, below that produced by the conch and consistent with the cave's length. Measured acoustics enable the tuning and verification of computational acoustical models, a new research direction that will be used to produce auralization demonstrations of the conch in its cave.

Musical Acoustics for Archaeological Interpretation

Archaeological interpretations are based on inferences from converging material evidence of past human activities. One way to deal with mysteries in the archaeological record is to evaluate functionalities of assembled materials according to what can be known about where, how, and by whom they were used. Musical acoustics offers methodologies for these investigations, such as that of

Figure 6. *ISO-3382 room acoustics metrics (analyzed using RØDE Fuzzmeasure software) applied to impulse-response data collected at human head height in front of the central bison painting in the Marsoulas Cave as shown in* ***Figure 5****. Reverberation time (T30) is shown, with good agreement across the four channels of the first-order Ambisonics (FOA) microphone (Zoom H3VR) that recorded the impulse responses that were generated via exponential sinusoidal sweeps through a portable omnidirectional loudspeaker (Bose Soundlink Revolve+). Values from the four cardioid outputs of the FOA microphone are plotted (****colored lines****) along with their average values (****black line****).*



the small perforation through the spire of the Marsoulas conch (**Figure 3**). From a functional point of view, a hole of this size was not required to make the conch sound. If somewhat larger, the aligned holes through two internal turns would be expected to disrupt sound propagation and reflections within the conical bore (Wolfe, 2020; Campbell et al., 2021). However, because of their small diameter, these two internal holes neither improve nor prevent the horn's sounding. Although such a small perforation would not enable the attachment of an external mouthpiece, tests demonstrated that a small bone, like the bones from birds that have been used to produce some Paleolithic flutes (Atema, 2014), can be fit through the Marsoulas conch's open spire and the two aligned holes. Whereas a small-diameter tube is not optimized as a mouthpiece extension, one hypothesis is that the interconnection of a bone flute with a conch shell horn would constitute an amalgamation of sound-producing instruments used during the Upper Paleolithic, a feature that could be seen as evidence for human experimentation in joining together different musical tools. Analogous to a visual expressive culture that appears to mix features of species in some cave paintings, musical instruments created from parts of different animals could be likewise formally combined. This anthropological hypothesis about craft production is supported by the musical acoustics research that shows that the bone-conch amalgamation, although not optimal for sounding, does not prevent the conch from being used as a lip-valve instrument/natural horn.

Archaeology and acoustics can be interrelated to explore the visual-expressive connection between the Marsoulas conch and the cave from which it was excavated. It is notable that the curved interior of the shell's lip and the walls of the cave where the shell was recovered were treated with a similar pigment application technique (Fritz et al., 2021). The similar painting of the shell's interior and its cave's interior suggests a deliberate human linkage of multisensory materials. Acoustical science can be used to explore the physical interaction potentials of the shell horn in relationship to the cave from which it was excavated and to evaluate and demonstrate multimodal interrelationships. The preliminary acoustical study of the Marsoulas Cave provided an initial documentation of its spatial acoustics as well as insights regarding sonic features at the location of its central bison panel, whose red-dot painting technique parallels the markings inside the lip of the Marsoulas conch. Acoustics, archaeometrics, and anthropology together inform a developing archaeological narrative about a place where music and visual art seem to have been made together 18,000 years ago. Further research will enable interpretations that can be experientially demonstrated by virtually joining visual art and music reconstructions in spatial context.

Musical Directions for Rock-Art Acoustics

Acoustical explorations between musical instruments and the proposed locations of their sounding offer exciting possibilities for new archaeological investigations, as detailed in this overview of the Marsoulas conch and cave study. By documenting the acoustical features of the associated conch and cave, this study takes an approach distinct from precedents in rock-art acoustics, including studies of open-air sites and caves, that can be summarized according to a dominant premise. Following the initiation of research on sound in decorated caves that employed human vocalizations to evaluate resonance effects (Reznikoff and Dauvois, 1988), acoustical measurements in rock-art sites have been conducted to search for patterns of similar acoustical features across locations of artworks (Fazenda et al., 2017). More recent research has sought to relate the acoustics of a painted cave facsimile to the acoustics of an actual cave, the well-known Lascaux Cave, with similar attention to noted sound effects (see archeologie.culture.fr/lascaux/en).

> "Early visitors of the original Lascaux cave were impressed by some unusual acoustical effects. They observed the relative silence in the cave, which led everyone to instinctively reduce voice levels while entering. Then the soundscape gives the impression that some animals are shouting, running, talking..." (Commins et al., 2020, p. 919).

Similarly, leading research in rock-art acoustics continues to focus on the documentation of human-observed sound effects in acoustical and auditory perceptual terms to connect spaces with human experience (Mattioli and Diaz-Andreu, 2017). The study of rock-art site acoustics has been positioned as a problem for methodological development (Diaz-Andreu and Mattioli, 2017), and the Marsoulas study calls attention to a new research domain for both open-air and enclosed rock-art sites, considering the interrelationships of distinct modes of expressive cultural production without an emphasis on particular sound effects and instead proposing multimodal explorations of acoustical context and interaction features. Music archaeology, despite its ephemeral topic, can be studied by relating sound-producing instruments to plausible sites of their use that are better known for visual-expressive culture.

Exploring the mechanics of archaeological materials, objects, and structures was once only a possibility through direct testing and experimental reconstructions of instruments using archaeologically substantiated materials and techniques. Now, in addition to physical experimental methods, computational acoustical models enable virtual testing and reconstructions beyond the creation of three-dimensional (3D)-printed replicas that can be produced for aerophones in particular (Katz, 2016). Acoustical measurements of sound-producing instruments and associated spaces provide data to drive computational models and verify these archaeological reconstructions, with direct applications in auralization simulations. Acoustics research opportunities abound in both fieldwork and virtual domains!

Music Archaeology into the Future

Although musical content cannot be recovered from most material remnants of past life, except in the case of materials with musical notation and, more recently, audio recordings, new approaches to music archaeology leverage physics. How instruments work and how their acoustics interact with performance settings can be tested experimentally (Kolar, 2020), related to performance-setting acoustics (Boren, 2021), and, for landscape contexts, estimated using geographical information system (GIS) tools (Witt and Primeau, 2019). These reconstructive explorations can be shared with public audiences via both data visualizations and auralizations, combining cultural heritage spatial acoustics (Katz et al., 2020) with anthropological treatments of sonic communication in the form of music. Cross-disciplinary collaborations unite the distinct areas of expertise required in relating materials and mechanics to human expressive culture. For example, the pioneering European Music Archaeology Project (see emaproject.eu) produced novel explorations of archaeological sites, including caves (Till, 2014), with a musical focus, featuring creative reconstructions of music performed in archaeological acoustical simulations.

The Marsoulas conch and its Magdalenian resting place in the Marsoulas Cave in southern France offer unprecedented physical evidence of the interconnectedness of visual art making and music. Acoustical science has enabled a functional evaluation of this proposed ancient musical instrument and provided empirical means for characterizing the sounding relationship of the shell horn with a likely context for its performance, despite 18,000 years of silence. Around the world, recent integrations of acoustics and auditory science research in music archaeology are revealing new evidence about sonic expressive culture throughout time. Acoustical methodologies hone the re-sounding of materials and places of importance in past societies, enabling physics-based explorations of music archaeology for audiences today.

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Rainfall at Sea: Using the Underwater Sounds of Raindrops as a Rain Gauge for Weather and Climate

Barry B. Ma, Brian D. Dushaw, and Bruce M. Howe

Rain on Land, Rain at Sea

Were you out walking when it starts to rain, you might take shelter in a shed with a tin roof. By listening to the sound of the raindrops plunking on the roof, you could tell that it is raining, how much it is raining, the size of the raindrops, and when the rain has stopped.

Listening to raindrops over the ocean surface using a hydrophone is analogous to listening to the rain under a tin roof. Raindrops hitting the sea surface generate loud sounds underwater. The ocean conducts sound very efficiently so that the sounds from the sea surface propagate down with little loss of energy; the sound environment of the ocean is much like a large echo chamber. The nature of the sound is unlike the plunking on a tin roof, however. Rain over the ocean sounds like the hiss of white noise underwater (Discovery of Sound in the Sea: Rainfall; see bit.ly/3KoN55m), with frequencies that extend well above the threshold of human hearing. In this article, we describe how those sounds convey considerable information about the nature of rainfall at sea.

Rain is, of course, intermittent in both time and location and has a wide variety of characteristics, ranging from light drizzle to heavy tropical downpours. On land, it is relatively easy to measure: a simple cup placed in the open for an interval of time can be used to determine the rate of rainfall. At sea, however, rain is difficult to measure because the ever-present sea spray can be confused for rain and a rain gauge can be violently disturbed by the confounding effects of waves. These difficulties, together with the obvious underwater sounds from rain, have led to the development of an acoustic rain gauge. Deploying an instrument at sea still faces the perennial problem of requiring some platform to put it on, however.

It might appear that the measurement of rain through acoustics would be challenging because there are many contributors to noise in the ocean. The sound environment can be complicated, and all ocean ambient sound is time, frequency, and location dependent. But rain is one of the major natural sources of underwater sound, and when rain is present on the ocean, its sound usually dominates all other sound sources. The dominant sound of rainfall, which occurs in the acoustic frequency range from 1 to 50 kHz, can be used to infer rain rate, accumulation, and the size of the drops themselves.

Why Listen to Rain?

Knowing the distribution of rain is necessary for weather forecasts in day-to-day life and is an essential variable for climate studies. Still, the accurate measurement of rain is an important challenge for climate science. Although it is essential to know the rainfall accurately, the quality of data from the rain gauges on at-sea moorings is poor. Satellite-based remote sensing can also measure the rainfall over the ocean, these measurements provide large-scale coverage of rainfall parameters such as rain rate and accumulation. However, satellite data cannot be used to determine the local variability and details such as drop size distribution.

Because of the great value of having data on the rainfall over the expanses of the oceans, novel methods had to be developed to get accurate measures. Through developments described in this article, acoustic rain gauges have been designed for practical, cost-effective deployment on many observation platforms.

Over the past quarter century, the oceanographic community has been developing the Global Ocean Observing

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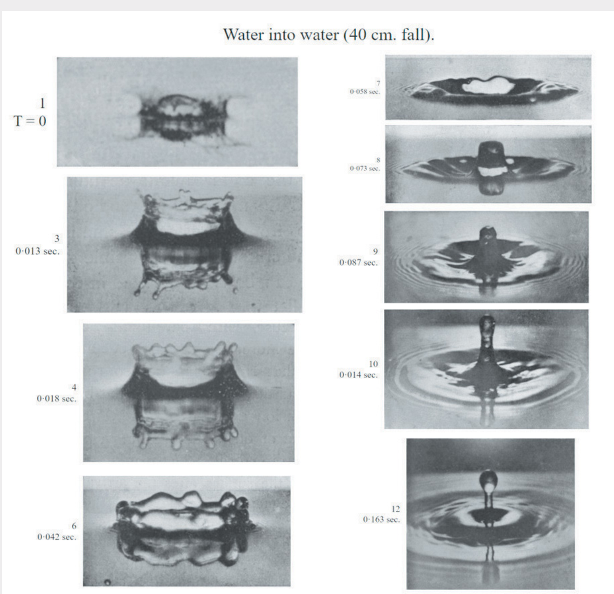
System (GOOS; see goosocean.org). Recognizing the importance of oceanographic information for society on the one hand (tsunamis, El Niño events, climate) and the difficulty and expense of obtaining oceanic data on the other, the GOOS comprises a variety of shared, sustainable platforms, from autonomous floats to long-term moorings to scientific cabling systems across the sea floor and terminating on shore. The availability of these platforms means that the acoustic rain gauges have the potential to become ubiquitously deployed rain gauges for global ocean coverage. In addition, the measurement of ocean sound is recognized as an essential ocean variable for GOOS, and the hydrophones of the rain gauges can be employed to measure sound generally.

A Bit of History

The nature of splashes of droplets hitting a water surface is a surprisingly complicated subject that has long attracted scientific interest. More than a century ago, photographs were used to describe the detailed process by which droplets strike the water surface. In that process, a drop will often create a small, temporary crater, splashes, or waves on the water surface. More importantly about rain-producing sound, a raindrop will often also form a cavity or entrain a small bubble of air when it enters the water. The phenomenon of a drop striking a water surface is controlled by surface tension or the attractive forces of liquid molecules along the water surface. The book by Worthington (1908), *A Study of Splashes*, has beautiful images of droplet splashes (**Figure 1**).

Figure 1. *A series of photos shows the impact process of a droplet falling into the water at different times starting at time (T) = 0. After the initial impact (1), a crater is formed and the crown-shape ring rises (3 and 4) and falls (6 and 7). Then a central column emerges (8 to 10), with ripples propagating outward (12). Adapted from Worthington (1908). Available at bit.ly/3Cq4aZS.*



Medwin and colleagues (1992) used an abandoned vertical utilities shaft with an anechoic tank at the bottom to build a unique facility for raindrop sound research. Rainfall could be simulated because the shaft was a 26-m-tall air chamber that allowed falling water drops to reach terminal velocity. Using this shaft, distinctive underwater sounds of different drop sizes and their drop splashes could be examined. They could also identify the different acoustical characteristics of the drop sizes (Medwin et al., 1992). Concurrent field studies developed the use of underwater sound to detect and quantify rainfall (Nystuen, 1986). From this work, passive acoustic instruments were developed to use the oceanic ambient sound field to measure rain rate, drop size distribution, and other properties (Nystuen, 2001). Such instruments are called "passive" because they do not require deploying an "active" acoustic source.

Extracting the Rain Signal from Noise

Ocean ambient sound originates from two basic sources: the activities of humans (anthropogenic sound: shipping, pile driving, construction) and nature (rain, wind, wave breaking, fish, marine mammals, earthquakes). Different sources of ocean ambient sound contribute to the overall sound level in different frequency ranges; here, we need only concern ourselves with the sound from the wind or rain.

Oceanic ambient sound is measured by a hydrophone mounted on a suitable platform that provides power for data sampling, recording, storage, and transmittal. At any given time, the local acoustic pressure fluctuations (in micropascals [μPa]) measured by a hydrophone result from the total contributions of the myriad sounds of the ambient environment.

For a given frequency, the contributions to the pressure fluctuation from different sources cannot be distinguished. But if sources have unique frequency spectra (sound pressure level frequency), then the times when only those sources are

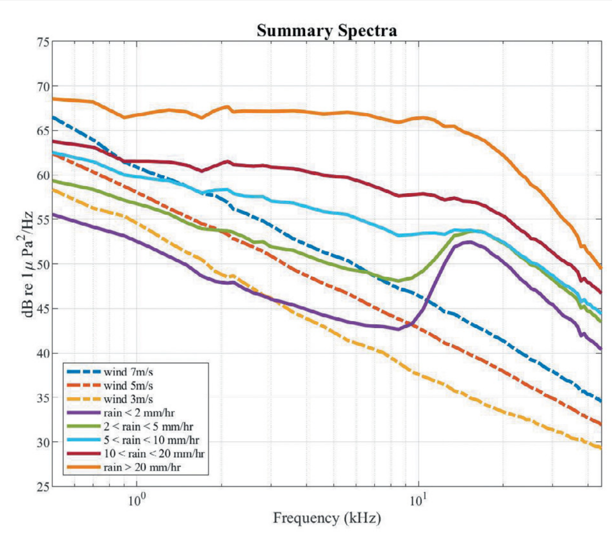


Figure 2. *The spectra of ambient sound during times of only rain or only wind. The data were collected from 14 open ocean locations over 90 months (Ma and Nystuen, 2005a), © American Meteorological Society, used with permission.*

present can be identified. For example, the noise generated by the wind is the major persistent noise component over the frequency range from 1 to 50 kHz, characterized by a simple spectrum that decreases with increasing frequency by about 16 dB per decade. When rain is present, however, the sound it generates usually dominates all other sources in that frequency range. When measuring rain, the dominant sound source is a signal that can be used to determine the properties of the rain. For example, the sound spectra of ambient sounds from wind only, rain only, and combined rain and wind are distinctly different (**Figure 2**) (Ma and Nystuen, 2005a). Importantly, the separate spectra of wind and rain in a combined spectrum can be distinguished by considering spectral slopes and relative spectral levels across different frequency bands.

Effective Listening Area

The underwater noise caused by wind and rain comes from the ocean surface. The sound intensity at a particular depth below the surface is a summation of all the contributions of sound created at the surface. The rainfall rate can therefore be obtained from a measurement of sound at depth because that sound is composed of all the sounds from the surface. In such a measurement, the sound sources are assumed to be uniformly distributed over the surface. If the absorption and refraction of sound are neglected (in practice, just minor corrections), the rainfall measurement is independent of depth.

Although the summation of surface sounds is theoretically over the entire ocean sea surface, as a practical matter, the effective listening surface area has a radius only three times the hydrophone depth; sounds from beyond that radius make only minor contributions. Thus, an instrument located at a 100-m depth samples an area with a radius of 300 m or roughly 0.28 km^2. Importantly, the measurement is inherently integrating over area, producing a spatially averaged rainfall statistic. In addition, because the total sampling period of a single measurement is about 1 min, the sound from many individual raindrop splashes is quickly accumulated, providing a robust measurement (Nystuen, 2001).

Types of Rain Sounds: It's All About the Bubbles

Raindrops hitting the ocean surface generate acoustic signals in two ways: the impact on the surface and the tiny bubble entrained by the drop and pulled below the surface. Surprisingly, the bubble is the loudest sound source for most raindrops, not the impact. When a bubble is created, the pressure inside is not in equilibrium with the surrounding water. During the impact process, a bubble is pushed and compressed. The pressure of the trapped air increases as the bubble shrinks by these forces and it becomes higher than that of the water. After shrinking, the bubble then expands, decreasing its pressure. In this way, a bubble oscillates between high and low pressure, a rapid process reaching an equilibrium at a high frequency and creating a unique sound at the bubble's resonant frequency. The bubble is "ringing," much like a bell rings. The sound radiates energy so the fate of the bubble is to lose its energy and reach equilibrium with the surrounding water.

The next thing to keep in mind is that the resonance (ringing) frequency of a bubble depends on its radius and the local pressure and water density. The resonance frequency is inversely proportional to the size of the bubble, so the smaller the bubble, the higher the resonance frequency (the higher the pitch of the sound). This quite accurate relationship was defined nearly 90 years ago by Minnaert (1933).

Of particular importance in the context of a gauge for ocean rain, bubble size is determined by drop size. If

Table 1. *Acoustic raindrop sizes and corresponding types of bubbles generated*

Drop Size	Diameter	Sound	Frequency Range, kHz	Bubbles Generated	Splash Character
Tiny	<0.8 mm	Silent		No	Gentle
Small	0.8-1.2 mm	Loud bubble	13-25	Type I	Gentle Bubbles every splash
Medium	1.2-2.0 mm	Weak impact	1-30	No	Gentle No bubbles
Large	2.0-3.5 mm	Impact Loud bubbles	1-35 2-35	Type II, III	Turbulent Irregular bubble entrainment
Very large	>3.5 mm	Loud impact Loud bubbles	1-50 1-50	Type II, III	Turbulent Irregular bubble entrainment Penetrating jet

Raindrop sizes are identified by different physical mechanisms associated with the drop splashes. Table from Ma and Nystuen (2005b).

rain were to consist of drops all the same size, those drops would all form bubbles of identical size, and the spectrum of the sound from such a hypothetical rainfall would have a peak at the resonance frequency of the bubbles. Conversely, if the frequencies of the spectral peaks in the sound of rain can be determined, the associated raindrop sizes can also be determined. Three types of bubbles generated from raindrops and their sound characteristics have been identified (**Table 1**).

Type I bubbles are generated from small raindrops. The impact component of the small raindrops is very quiet, and each such raindrop predictably generates a small type I bubble (Pumphrey et al., 1989). The frequency range of these bubbles is a high resonant frequency that Medwin (1990) called a "screaming infant."

Type II bubbles are generated by large and very large raindrops. A large raindrop creates a large, primary, type II bubble that occurs about 50 ms after the drop impact (Medwin et al., 1992).

Type III bubbles are also generated by large and very large raindrops. Large drops form an impact crater in the surface so large that tiny droplets are ejected into the air (Nystuen and Medwin, 1995). The reentry splashes of these tiny droplets produce secondary bubbles. These secondary, type III bubbles are delayed, occurring more than 100 ms after the initial drop impact. Because of the wide range in bubble size formed by the droplets, the frequency range of these bubbles is wide.

Drizzle (light rain) has a unique signal because it consists of small 1-mm raindrops and no large raindrops. Heavier rainfall, containing both large and small drops, produces very loud sound levels across a wide frequency range (Nystuen et al., 1993). Breaking waves also produce sound from bubbles. The distributions of bubble sizes produced by breaking waves and raindrops are quite different, however, so that the sound source, whether wind, waves, rain, or drizzle, can be distinguished by the distinctive spectral characteristics of the recorded sound.

The Effect of Wind on the Sounds of Rainfall

The presence of wind during rain can affect the sound signals created by the drops, depending on wind speed and drop size. Wind causes the rain to slant as it approaches to the sea surface, and it affects the splash of the interaction at the surface. The effect has been studied in laboratory experiments that assessed the chances that an individual drop blown by wind will produce a bubble, creating a measurable sound. Those chances decrease linearly from 100% for normal incidence (rain falling straight down) to 10% for oblique incidence (rain falling at a 20° angle from the vertical) (Nystuen, 1993). The wind naturally has a

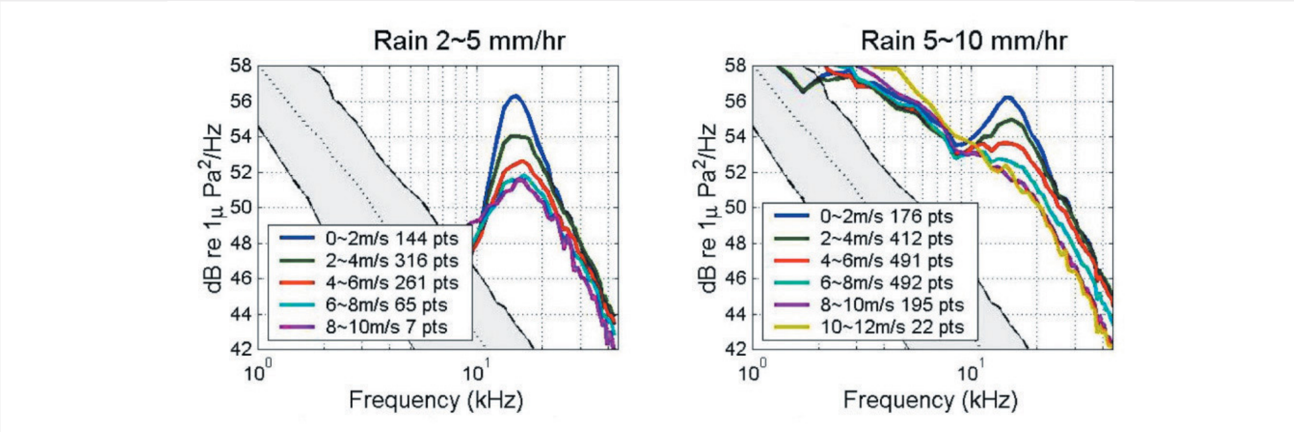


Figure 3. *The average sound spectra for rainfall rates of 2-5 (**left**) and 5-10 (**right**) mm/h are decomposed into various wind speeds. **Gray area**, wind-only spectra; **dashed-dotted** (left), **dotted** (center), and **dashed** (right) black lines, average spectra for wind speeds at 2-4, 4-6, and 6-8 m/s, respectively; **numbers in box**, number of data points in each category (Ma and Nystuen, 2005b). Increasing wind speed causes decreasing sound levels in a predicable way.*

greater effect on smaller raindrops, so the sound signal from drizzle is highly sensitive to wind speed. The wind appears to suppress the bubble creation mechanism of small raindrops, with the rain-generated sound at around 15 kHz inversely proportional to the wind speed (**Figure 3**). For larger raindrops that generate sound in the 2- to 8-kHz frequency band, the sound level is relatively insensitive to the wind speed. The bubble-trapping mechanism for large drops appears to be insensitive to the angle of impact (Ma and Nystuen, 2005b). To develop corrections for wind speed in acoustic rain gauges, rainfall spectra have been classified for various wind speeds using coincidental acoustic and wind speed data obtained during rain events.

Acoustic Rain Gauges

The need for better measurements of rainfall rates at sea and the ability to make such measurements by recording ambient-noise spectra led to the development of acoustic rain gauges (ARGs), later renamed Passive Aquatic Listeners (PALs) by Nystuen et al. (2015) (**Figure 4**). Nystuen received the Medwin prize from the Acoustical Society of America (ASA) for this work in 2003 (Ma and Leopold, 2021). The PAL was a self-contained, low-power acoustic recorder that could estimate and store acoustic spectra every minute over year-long periods. The PAL data-collection sequence consisted of first obtaining four 10- to 24-ms time series sampled at 100 kHz at 5-s intervals, from which power spectra were computed (0-50 kHz). These spectra were averaged and compressed to 64 frequency bins, forming the 1 rain measurement.

The PAL recorded spectra at 1-min intervals during rainfall events and 8-min intervals otherwise. When rain or drizzle signals were detected, determined by obtaining

Figure 4. *Jeffrey Nystuen and a self-contained Passive Aquatic Listener designed for deployment on a mooring in 2001.*

rain-type spectra with a minimum threshold in sound pressure level, the spectral data began to be saved at 1-min intervals. Assumed rain spectra were then collected at 1-min time intervals until no rain was detected. After a rain event stopped, a longer sampling time interval of 8-min was used, and the stored spectra were labeled as wind spectra. This sampling scheme made it possible to record acoustic spectra over the long term using the computer-embedded system technology available around 1990 when the PAL was developed. The acoustic rain measurement proved to be a success, and measurements that were equal to or better than other automatic rain gauges. Other rain gauges employed a variety of methods, including weighing, capacitance, tipping bucket, optical, or disdrometer methods (Nystuen et al., 2000).

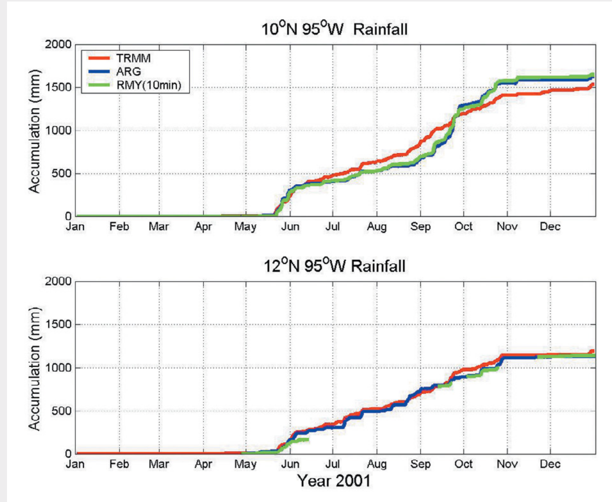


Figure 5. *Rainfall accumulation measurements at two locations from acoustic rain gauge (ARG), R. M. Young company surface rain gauges (RMY), and satellite estimates from the Tropical Rainfall Measuring Mission (TRMM) of precipitation at two deep ocean moorings in the equatorial Pacific. Fouling and other problems caused some loss of data for the RMY rain gauge at 12°N. The accumulation data for RMY are offset to match the ARG accumulation after periods of nonperformance. Adapted from Ma and Nystuen (2005a), © American Meteorological Society, used with permission.*

Rain Detection and Quantification

The spectra data collected by the PALs need to be processed after data recovery to obtain a refined, precise detection and characterization of rain events while eliminating false alarms or events not related to rain. A series of tests were devised to eliminate spectra inconsistent with natural ambient sound and to identify spectra consistent with known types of rain.

The screening process removed two types of noise. The first was associated with "bangs" when one of the four spectra was much louder than the other three. Such events might occur when a wave slaps on the hull of the surface buoy. The second test, like that used to detect wind noise, used the shape of the recorded spectrum to eliminate sound spectra that were not consistent with known rainfall signals.

Another set of criteria was developed to use the unique spectral and temporal characteristics of the different types of rainfall to detect the presence of precipitation (drizzle or rain). The acoustic data were divided into spectra with drizzle or rain detection and wind detection, based on characteristics consistent with rain or wind spectra. Once a rainfall signal was detected, the spectral amplitude was used to estimate the instantaneous rainfall rate, which can be quantified using a simple relationship to sound intensity. Measurements of rainfall accumulation obtained this way agree well with satellite and buoy rain gauge measurements on seasonal timescales (**Figure 5**).

Inversion for Drop Size Distribution

A rain event's drop size distribution (DSD) characterizes rainfall by describing the number of drops per unit volume per drop size bin. From the DSD, useful properties such as liquid water content, optical cross-section, rainfall rate, or radar reflectivity can be calculated (Nystuen and Amitai, 2003). Furthermore, different rainfall types such as stratiform (a heavy downpour) or convective (a persistent light rain) can be identified by the DSD (Atlas et al., 1999).

Because of the different sound-generating mechanisms present for different raindrop sizes, categories of DSD can be defined acoustically based on the mean acoustic energy per drop for different raindrop sizes. The DSD is computed from the acoustic data via an inversion using standard techniques. The approach is based on using an empirically determined transfer function that relates simultaneous acoustic field measurements and DSD measurements.

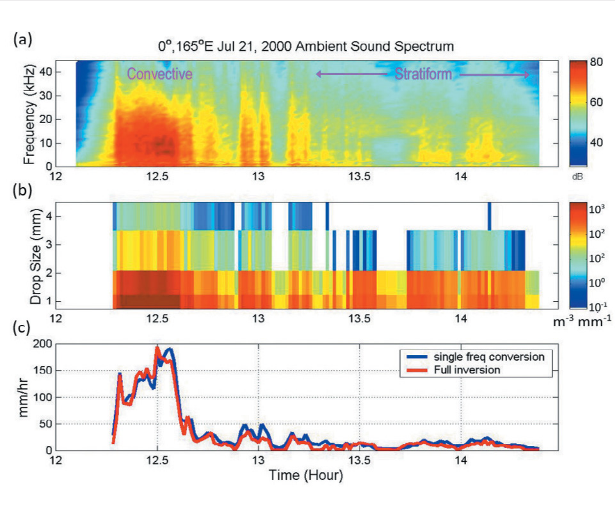


Figure 6. *The ambient ocean sound from 0, 165°E.* ***a:*** *Convective rain produces strong sound signals from 1 to 35 kHz. The stratiform rain (drizzle) has a peak signal at 15 kHz.* ***b:*** *Drop size distribution (DSD) using acoustic inversion.* ***c:*** *Rainfall rate is derived using the single-frequency conversion and full-inversion methods.*

Nystuen (2001) first computed an acoustic inversion for the DSD based on field data collected in a shallow brackish pond in Florida. Applying the same inversion algorithm to open ocean data required a frequency-independent adjustment of the transfer function (accounting for shallow-water reverberation in the pond and a lower initial acoustic pressure of large bubbles in saltwater compared with freshwater). When new methods to measure the DSD directly in the open ocean are developed, a new transfer function can be calculated.

The DSD rainfall estimates based on the sound-intensity relationship and inversion diverge as rain changes from convective to stratiform. The simple relationship between sound intensity and rain rate implicitly assumes a DSD shape typical of convective rainfall. Stratiform rainfall has relatively fewer small- and medium-sized raindrops, and thus the sound-intensity relationship overestimates stratiform rainfall rates. Using the DSD inversion method improves the agreement between acoustic DSD estimates and surface rain gauges. The result suggests that the full DSD acoustic inversion for rainfall rate should be used when mixed stratiform/convection rainfall events are being measured acoustically (**Figure 6**).

More Platforms for Collecting Passive Acoustic Data

Over the last two decades, advanced observation platforms entered service to survey the global ocean, all of which could be considered components of GOOS. The need to remotely sense the air-sea interface from underwater led to the addition of hydrophones to collect ocean ambient-noise data. Besides the moorings that have hosted PALs, various autonomous platforms have been developed for acoustic rain and wind measurements, including Argo floats (Yang et al., 2015), seagliders (Ma et al., 2018), and cabled seafloor observing systems. These platforms provide near-real-time acoustic spectra data and some also record raw acoustic time series, which offers opportunities to extract useful ocean information using passive acoustic methods.

Seagliders are underwater autonomous vehicles about 2 m in length that use internal changes in buoyancy to "drive" the vehicle to cycle up and down in the water column. The seaglider has small, fixed wings that cause it to move horizontally as it moves up and down. As a result, a seaglider glides horizontally while zigzagging up and down, usually between the surface and 1,000 m in depth. At the surface, the seaglider uses satellite communications to send its data back to shore.

In an experiment in the tropical Pacific (Lindstrom et al., 2017), ambient-noise data were acquired using a hydrophone system on the seagliders. The acoustic data were processed and averaged into 7 frequency bins from 1 to 55 kHz and transmitted to shore. Using the rule-based detection method, various rain and wind conditions were distinguished and classified using ambient-noise spectra shapes. Rain noise was still detected acoustically to 1,000 m, the maximum depth of the seaglider (**Figure 7**).

To test the validity of the seaglider data, simultaneous rain measurements were obtained from a buoy rain gauge and satellite rain rate products. The comparison showed small discrepancies between different measurement methods due to differing spatial and temporal sampling schemes. Although it was difficult to compare rainfall rates and rain events, the seasonal accumulations were in agreement. The instantaneous acoustic method has advantages (higher temporal resolution and larger effective surface-sampling area) compared with conventional rain gauges.

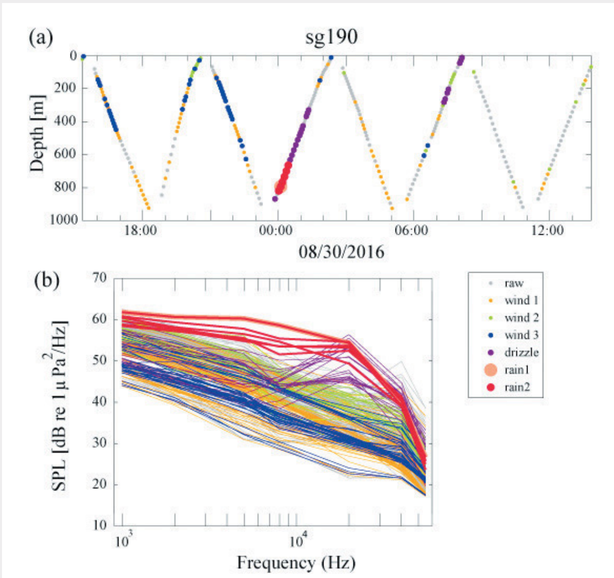


Figure 7. ***a:*** *Seaglider (SG-190) profiles during a field experiment at 10°N, 125°W.* ***b:*** *Acoustic spectra of wind and rain were identified using rule-based algorithms.* ***Color dots*** *in* ***a*** *correspond to* ***color spectra*** *in* ***b*** *and indicate the detection of wind and rain according to various detection rules (wind 1-3, rain 1-2, and drizzle). SPL, sound pressure level; raw, no rain or wind.*

The challenges for the acoustic method are that it is passive, it relies on correct amplitude calibration, and other sources of ambient sound can affect acoustic data quality.

The Future

To a large extent, the development of the Ocean Observing System has resolved the perennial problem of available platforms to hang a rain gauge on at sea. In addition, a cabled observing system across the seafloor provides a constant stream of real-time data from passive acoustic sensors located both on the seafloor and in the water column. These systems, which are cabled to shore, allow real-time data access from the comfort of one's home. Rainfall signals can be extracted from the acoustic data stream from a cabled hydrophone system (Schwock and Abadi, 2021). These observations, employed for scientific studies or monitoring beyond the rain measurements, align with the concept of multipurpose acoustic systems suggested by Howe et al. (2019). The adoption of general-purpose acoustic receivers can serve the scientific community interested in passive acoustic monitoring.

Ocean sound as an essential ocean variable (Miksis-Olds et al., 2018) is gaining more visibility and traction in the global ocean-observing community. For instance, the MERMAID program (Nolet et al., 2019; Simons et al., 2021), a project of the *United Nations Decade of Ocean Science for Sustainable Development 2021–2030*, developed floats for hydroacoustic monitoring of earthquakes. Float capabilities are now being extended to general purpose use, including rain and wind measurements and marine mammal detections.

The original PAL was developed to provide a consistent, reliable, and self-contained long-term recorder. It stored spectra and very short sound bites (seconds) only to ease the computational burden of data processing. The lack of complete time series, however, limits the ability to distinguish transient noises either from platform self-generated noises or unidentified sources. A 1-month acoustic time series, sampled at 120 kHz, requires several terabytes of data storage, which is now readily available. Such large datasets are helpful to dissect the transient sounds that may harbor new discoveries. Some of the advanced autonomous platforms of Ocean Observing Systems can transmit processed data in near-real time, but they are limited by onboard power storage and data bandwidth. It is an art to balance all the factors to decide when, what, and how to process and transmit useful ocean environmental data. The challenge of vast datasets may be addressed with machine-learning applications that may reduce dimensionality and cluster and classify acoustic source data (Bianco et al., 2019), perhaps allowing Nystuen's vision (hearing) to reach its full potential.

We hope to develop next-generation instruments for new passive acoustic rain measurements specifically and for high-frequency sound monitoring generally, exploiting all the recent advances. Such instruments would be designed to be deployed on any of the several platforms available from operational Ocean Observing Systems.

Acknowledgments

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Conversation with a Colleague: Joseph A. Sisneros: The Soniferous Life of Midshipman Fish

Joseph A. Sisneros
Conversation with a Colleague Editor: Micheal L. Dent

Figure 1. *Joe Sisneros with a plainfin midshipman.*

Meet Joseph A. Sisneros

Joseph A. (Joe) Sisneros is the first subject of our new "Sound Perspectives" essay series "Conversation with a Colleague." Joe is currently a professor in the Psychology Department at the University of Washington, Seattle (see sisneroslab.org). He received bachelor's and master's degrees from California State University, Long Beach, California, and his PhD from the Florida Institute of Technology (FIT), Melbourne. He completed his postdoctoral training at Cornell University, Ithaca, New York. Joe is a Fellow of the Acoustical Society of America and serves as an associate editor for *The Journal of the Acoustical Society of America*. We asked Joe to give us his elevator pitch and then to elaborate on his inspirations, contributions, and hopes for the future.

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

How well can you hear? If you are like me, a middle-aged person, you may have trouble hearing high-frequency sounds or have difficulty being able to discriminate certain sounds in a loud room. What if I told you that the fish that I study may "hold the key" to improving hearing in older humans? My lab is interested in how steroid hormones such as testosterone and estrogen enhance hearing sensitivity to high frequencies within an animal's hearing range.

We study the plainfin midshipman (*Porichthys notatus*), a vocal fish that is highly dependent on the production and reception of acoustic signals for its social behaviors (**Figure 1**). Thus, it has become a good model species to investigate the neural basis of acoustic communication. Female midshipman rely on their auditory sense to detect and locate calling males during the breeding season. Work from our lab has shown that females exhibit reproductive-state and hormone-dependent changes in the auditory sensitivity of the saccule, the main organ of hearing in the midshipman and most other fishes, such that reproductive females are better able to hear the advertisement calls of potential mates than nonreproductive females. The primary mechanism for this reproductive state-dependent change in hearing sensitivity is estrogen. In support of these findings, studies of human and rodent females with Turner's syndrome, a genetic aberration that results in the loss of ovarian estrogen production and decreased estrogen-receptor expression in the cochlea, show that females with this syndrome exhibit a progressive loss in high-frequency hearing with development. These mammalian studies support the link between estrogen and high-frequency hearing sensitivity. Might circulating levels of estrogen

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and testosterone be involved in the maintenance of high-frequency hearing sensitivity in humans? Studies of the effects of estrogen on midshipman hearing might provide the answer someday.

What inspired you to work in this area of scholarship?

I became inspired to work in the research area of hormones and behavior during my PhD working in the lab of Timothy "Tim" Tricas at FIT. I had the opportunity to travel to Mexico with Tim to investigate the role of electroreception during mating in the round stingray (*Urobatis halleri*).

We found that male stingrays use their extremely sensitive electric sense to detect and locate reproductive females buried in the shallow lagoons, which were the breeding grounds for this species. Females emit a complex weak bioelectric field from their gills that is modulated during ventilation by the rhythmic movements of their gill slits and spiracles (a muscular valve that intakes water into the gill chamber). We discovered that the electroreceptor system of male stingrays was "tuned" to 1-2 Hz, which matched the low-frequency "signature" signal produced by buried females during ventilation. This matched filter of the male's electroreceptor system with the female's electrical signal only occurs during the mating season when androgen levels are elevated. These studies that combined animal behavior and electrophysiology piqued my interest in learning more about the neural basis of behavior and initiated my career path on becoming trained as a neuroethologist.

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

Perhaps I am most proud of the research that was performed during my postdoc training in the laboratory of Andrew "Andy" Bass at Cornell University, Ithaca, New York. What started as an "odd observation" eventually led to an important discovery of the mechanism that is responsible for seasonal changes in hearing sensitivity in the plainfin midshipman.

The purpose of my postdoc was to work on the auditory system of the plainfin midshipman fish. My initial interests were to examine how the auditory sensitivity of the midshipman changes during development from early juvenile to adult stages.

During my first full summer in the Bass lab, I traveled to the University of California, Davis, Bodega Marine Laboratory in Bodega Bay to collect juvenile midshipman and characterize ontogenetic changes in the auditory sensitivity of the midshipman saccule. Unfortunately, I arrived too early in the summer season to collect fish that were large enough to obtain recordings from. This enabled an alternative fortunate opportunity. Instead of waiting around for my fish to grow large enough to record from, Andy suggested that I try to characterize the sensitivity of the saccule in adult females that had recently spawned and from females that were still gravid (full of eggs) to determine if the presence of eggs affected the auditory sensitivity of the saccule.

Earlier, Andy had shown in midshipman behavioral experiments that reproductive gravid females perform phonotaxis to the playback and sound source of a synthetic male midshipman advertisement (mate) call because gravid females are highly motivated to spawn. However, females that had recently spawned showed no interest in the call. Could it be that "spent" females (void of eggs) are just no longer motivated to respond to the call or could there be a change in their auditory sensitivity to the call?

As I started collecting data on the auditory sensitivity of saccule in reproductive females, I noticed something odd. The auditory tuning profiles of the saccule in reproductive females did not match the saccular tuning profiles that the Bass lab had obtained in a previous study on midshipman fish that had been housed over the winter back at Cornell. The saccule of reproductive females (whether gravid or not) appeared to have a greater sensitivity to higher frequencies within their hearing range compared with previous recordings of "winterized" fish. After many calibration checks and the retesting of my equipment, we concluded that it wasn't the equipment but something different about the fish!

Could there really be seasonal changes in midshipman auditory sensitivity related to the female's reproductive cycle? The observed seasonal changes in the electrosensitivity of adult elasmobranch fishes and in other fishes such as weakly electric fishes were one thing, but in the auditory system? Such changes in the auditory sensitivity of adult animals had never been documented before.

To test this, we would need to obtain female midshipman collected during the nonreproductive period and record from their saccules. I conspired with Paul Forlano, who was a graduate student at the time in Andy's lab and is now a professor at Brooklyn College, a campus of the City University of New York, and he helped me convince Andy to pay for a trip to collect winter, nonreproductive female midshipman in Monterey Bay, California.

The problem was that during the nonreproductive season, midshipman move offshore into deeper waters and can be found at about 80 to 100 meters deep. To collect midshipman at these depths, we needed to charter a boat and collect fish offshore using an otter trawl. We only managed to collect 22 nonreproductive females and sent them back to the Bass lab for auditory saccular recordings. After a few saccular recordings from those females, we arrived at that "Eureka" moment and realized that nonreproductive and reproductive females were tuned differently and that seasonal changes in the auditory sensitivity of adult animals did indeed exist!

Later, we found that the saccules of reproductive females were more sensitive to higher frequencies within the midshipman hearing range, which meant that summer reproductive females were better able to detect the higher harmonic components in the male advertisement call. This seasonal enhancement and plasticity of the auditory system likely enhanced the detection and location of potential mates by females during the breeding season.

The next big challenge was trying to determine the mechanism responsible for the observed changes in auditory sensitivity. Based on earlier work, including my dissertation research, we decided to investigate the role of gonadal steroids (androgens and estrogen) as potential modulators of auditory sensitivity. However, at the time, we had no idea about how gonadal steroid levels changed seasonally in the midshipman fish.

We decided to undertake a two-year study to document and characterize how androgen and estrogen levels changed during the midshipman reproductive cycle. This was not an easy task. It required us to collect blood samples and determine midshipman hormone levels at different time points throughout the year and correlate these changes with the seasonal development of the gonads in both males and females. We were able to characterize how androgen and estrogen levels changed during the annual reproductive cycle of both females and males. Interestingly, we noted that in females, both testosterone and estrogen levels were relatively low throughout the year except for one month prior to the breeding season, when females exhibited a spike in testosterone and estrogen levels. Could it be that these spikes in hormone levels were responsible for inducing the sensitivity changes in the saccule?

To determine if testosterone and estrogen were responsible for changes in auditory saccular sensitivity, we implanted winter nonreproductive female midshipman with either testosterone or estrogen to simulate the hormone levels that females naturally experience one month prior to the breeding season. Our results from the hormone implant experiments showed that nonreproductive females treated with testosterone or estrogen exhibited enhanced auditory saccular sensitivity to the dominant frequencies contained in the male advertisement calls. Furthermore, the saccular tuning profiles of the hormone-implanted females mimicked the saccular tuning profiles of summer reproductive females. This sensory plasticity observed in adult females was thought to provide an adaptable mechanism that enhances the coupling between sender and receiver in the midshipman communication system. Our work wound up being timely and was subsequently published in the journal *Science*. This study represents perhaps my most proud contribution to science and was truly a team effort in collaboration with Andrew Bass, Paul Forlano, and David Deitcher. Since the publication of this paper, the reported hormone-dependent mechanism appears to be evolutionary conserved with other studies reporting similar changes in sensory sensitivity due to gonadal steroids in adult animals from other taxa including amphibians, birds, and mammals.

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

These include the investigation of sound source localization by fishes, which was the topic of my first National Science Foundation grant as an assistant professor at the University of Washington. Previous evidence suggested that the capacity for sound source localization was common to mammals, birds, reptiles, and amphibians, but, surprisingly, it was not known whether fish locate sound sources in the same manner or what strategies they used for sound source localization.

Working with colleagues Richard Fay (see doi.org/10.1121/AT.2020.16.3.53) and David Zeddies, we showed that the midshipman use local particle motion sound cues to guide sound source localization behavior. All fishes are thought to be able to detect the particle motion cues of underwater sound using their inner ear otolithic end organs, which act as biological accelerometers to sense linear acceleration and respond to the direct displacement of water particles relative to the fish caused by sound. We showed that midshipman rely on their inner ear "accelerometers" to detect acoustic particle motion cues, which helps guide them to sound sources during localization behavior.

We also investigated the roles of the fish swim bladder and the lateral line system in midshipman sound localization behavior and showed that sound pressure reception via the swim bladder is likely required, whereas the use of the lateral line was likely not required for sound source localization. Currently, my lab is still very much interested in research on sound localization by fishes as well as the underlying neural mechanisms for these behaviors.

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

As I think about the big unanswered research questions in the field, it is apparent that we know very little about the cellular, molecular, and genetic mechanisms that are influenced by gonadal steroids and how these mechanisms ultimately modulate the sensitivity of auditory and other sensory systems. Future studies that examine how steroids such as estrogen regulate gene expression in the midshipman inner ear may eventually provide insight to the mechanisms responsible for hormone-dependent changes in hearing and other senses. This area of research seems to be the next frontier that bridges genes and behavior. Research in the not-so-distant future promises to be exciting. Stay tuned!

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From the Executive Director

Susan E. Fox

"You will come to a place where the streets are
not marked.
Some windows are lighted. But mostly they're darked.
But mostly they're darked.
A place you could sprain both your elbow and chin!
Do you dare to stay out? Do you dare to go in?
How much can you lose? How much can you win?"
(From Dr. Seuss, *Oh, The Places You Will Go*).[1]

Navigating the New

One characteristic that sets the Acoustical Society of America (ASA) apart from most professional societies is the exceptionally high regard that our members have for the Society. Multiple surveys confirm that in many members lives, the ASA serves as more than a professional home. The ASA became and is an intellectual, spiritual, and emotional anchor, a place where like-minded colleagues share purposes and values. This foundational community is so strong that it became our rock during this global pandemic.

Over the course of the past two years and still counting, the ASA anchored us, and as a community, we rose to meet challenge after challenge, united in our commitment to each other and the greater good. The ASA, I am pleased to report, is even more robust, resilient, and cohesive as ever before.

Challenges

The biggest and most immediate challenge involved deciding what to do about our spring 2020 meeting that was scheduled to take place in Cancun, Mexico. We had no choice but to cancel that in-person meeting that was eventually held virtually. The fall 2020 meeting planned for Chicago, Illinois, was also held virtually. Then-president Diane Kewley-Port appointed a Virtual Technology Task Force chaired by Andy Piacsek to assist us in considering options and strategies for mounting our first-ever set of all-virtual semiannual meetings. Given the complexities of securing and deploying a suitable platform and the very short period in which to plan, one fellow society CEO likened the exercise to "building a plane while you are trying to fly it."

Virtual platforms for holding a digital version of professional society meetings do exist so none of us were left completely in the cold. However, none of the platforms performed well, and there is a cultural disconnect between software engineers who develop these platforms and the functionality needed by the scholarly society market they wish to capture.

This added an additional stress point to our desire to pivot in a way that best serves our members. It was the commitment of the ASA leadership, members, and staff that brought us to the point where within eight weeks we managed to have a fully virtual spring 2020 meeting, Acoustics Virtually Everywhere (see acousticalsociety.org/overview-ave), including meetings of our administrative committees, a plenary session, and "social hours." It wasn't perfect by a long shot, but the postmeeting survey revealed understanding and patience on the part of our members. Importantly, we kept the work of the Society moving forward and we provided a way for us to connect as a community despite the many odds against us.

One would think that a virtual meeting would produce significant savings from the costs of producing an in-person meeting. One would think wrong. The cost of virtual platforms runs into the six figures. We saved some monies but not as much as one would expect. Unlike many societies, some of whom depend almost entirely on meetings for revenues, The ASA's fiscal stability is well established through journal revenues, a source of ballast and relative security as we navigate our way forward.

We learned a great deal from the Acoustics Virtually Everywhere meetings that we applied it to the next virtual meeting in fall 2021, Acoustics in Focus (see tinyurl.com/ya569f9r). With experience under our belt, this meeting ran a bit better

1 *Dr. Seuss,* Oh, The Places You Will Go. *Copyright 1990, Random House.*

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but not without challenges. Nonetheless, the postmeeting survey again revealed general satisfaction with the outcome, especially given the alternative of no meeting at all.

We held our first in-person postpandemic meeting December 2021 in Seattle, Washington. To keep everyone as safe as possible, we observed vaccination protocols and social distancing. After two years apart, the joy of convening together physically remained palpable throughout the week. With over 1,000 acousticians, our attendance figures paralleled those of "before times." By the time you read this, we will have held our second in-person meeting in spring 2022 in Denver, Colorado, with hopes that we are fully back on the road to recovery.

Of course, there were other challenges to the ASA aside from the necessity of reinventing meetings. After George Floyd's tragic death, we responded to the need to become even more sensitive to issues of diversity, inclusion, and equity by creating the Committee to Improve Racial Diversity and Inclusivity (CIRDI; see tinyurl.com/2p9duycx) cochaired by Tyrone Porter and incoming president Peggy Nelson. Through CIRDI, the ASA went on to establish a Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA; see tinyurl.com/3v7nsvsv).

SURIEA, a 12-week paid summer undergraduate research program for students interested in acoustics, is designed for underrepresented minority undergraduates from across the country. It provides training, mentoring, research, and preparing students for graduate studies and careers in acoustics.

Reflecting on the past 24 months I can't help but step back, rest a moment, and appreciate with gratitude our ability to respond to extraordinary events with extraordinary commitment and grace. We worked together as a team, and we are blessed with a long-tenured, deeply knowledgeable staff. In many ways, they are our unsung heroes: Nancy Blair-DeLeon, Jolene Ehl, Dan Farrell, Keeta Jones, Mike McGovern, Elaine Moran, Ambri Phillips, and Kelly Quigley.

Looking Forward

As you can see from these examples, the ASA community is undaunted by the unexpected. We are emerging much stronger, more aware, and more committed than we have ever been. We now begin the process of planning for the next strategic plan and how we will navigate a new set of unmarked, dark streets. An important part of that process, especially now, will be to conduct a trend anaylsis. Once we move past these times, what will our world look like? It's almost incomprehensible how much everything has changed: the labor force, geopolitics, global supply chains, business models, and on it goes. Our mission is to generate, disseminate, and promote the knowledge and practical applications of acoustics. What impacts post-Covid must we consider as we position the ASA to best serve the needs of acousticians in a fundamentally changed world?

Here are a few top line factors I'm personally following with an eye toward the future and what role the ASA can play to enhance or mitigate consequences:

- Women, early-career researchers, and students from disadvantaged backgrounds have been disproportionally affected by the pandemic. Early studies (see tinyurl.com/mr2ysdjp) show that across disciplines, the publishing rate of women has fallen relative to that of men amid the pandemic. Will this rate rebound or is this indicative of women and early-career researchers dropping out of field entirely? It's too soon to tell.
- A perennial on my radar relates to the act convening in all its forms and how that advances the collaborative work of science. Studies (see tinyurl.com/y633savt) suggest that we may need to rethink the programmatic design of scientific meetings. "...The way organizers design conferences can have a direct effect on which scientific collaborations are formed and, by extension, on the direction of scientific inquiry."
- Related: What will be the impact of advanced artificial reality (metaverse) (see tinyurl.com/ycknkhjf)? How will this affect and redefine meetings, if at all? Does form follow function or will it evolve into something else with form more in the lead?
- International cooperation and collaboration have always been valued in the ASA, but today they become even more important as we become a highly interdependent world. One-third of the ASA membership comes from outside the United States. Now that we have the technical means to involve members more effectively and broadly, what do we need to consider? How can we serve this part of our membership best?

- Environmental sustainability can no longer be ignored. What is the ASA's obligation to the planet? How do we promote and employ awareness and best practices as ASA members and citizens of the planet?
- One question has a permanent place on my radar: What do I need to be aware of that I'm not?

With these trends and others in mind, the future, although now foggy and fraught, presents as much opportunity as it does threat. I'm grateful to the thousands of people who as members support the ASA. I'm grateful to our staff, to our leadership, to you. I think of us as an ant raft, coming together in rough waters, connecting, constructing, emerging buoyant, and riding it out to the other side. To me, this is the meaning at the heart of resilience. In community, we win far more than we lose.

Onward!

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Social Media for Acoustics Professionals

Kathi Mestayer, Andrew Morrison, and Edward Richards

Introduction

Social media has begun to play a large enough role in our everyday lives that readers will probably have an opinion about its use. Although we realize that not all members of the Acoustical Society of America (ASA) use social media, we want to encourage everyone to consider its use for promoting acoustics research. The use of social media has grown in the Society since the first *Acoustics Today* article promoting its use (Farrell and Jones, 2017). Many of the benefits predicted by this first article are beginning to be realized by a small community of members, with many examples produced by the active participation of members of the Animal Bioacoustics Technical Committee. Society members use social media to promote and enhance research, teaching, and work programs in ways that are interesting, and we use examples to demonstrate some successes, with the hope of encouraging more participation.

In a world where we are constantly online, it is easy to just say "Is this worth doing? I mean, who has time for this?" However, although social media interactions may seem trivial, this engagement increases the camaraderie among researchers, especially in far-flung institutions, and increases the visibility of acoustics to the larger public. Increasingly, social media engagement provides a proxy for the interactions in scientific workplaces and conferences, providing a more continual engagement of a broader and more inclusive audience (Foell, 2021). Social media is emerging as an effective tool for promoting published content, answering acoustics questions, and conducting scientific outreach.

Acoustical Society of America Online Presence

The acoustical community has already begun to participate in social media. By far, the largest online community in acoustics is on Twitter (see twitter.com). The ASA has an active account on Twitter (@acousticsorg) with over 6,100 followers. Many of ASA's publications have Twitter accounts. *The Journal of the Acoustical Society of America* (*JASA*), *The Journal of the Acoustical Society of America Express Letters* (*JASA-EL*), and *Proceedings on Meetings on Acoustics* (*POMA*) are all well followed. In addition to its Twitter presence, the ASA has a public group on Facebook, with over 2,400 members, as well as a presence on LinkedIn and YouTube.

The simplest way to begin a new Twitter community is to build on lists of users interested in acoustics. A few examples of Twitter lists include a bioacoustics list (see tinyurl.com/4uhx5486), an applied acoustics list (see tinyurl.com/mpcjt46h), a list of acousticians (see twitter.com/i/lists/199306046), and another list of people and organizations who use acoustics in their work (see twitter.com/i/lists/195934686).

Utility of Social Media

The distinct formats of each social media platform help make scientific research accessible to broad audiences following different proven communication patterns. Twitter, LinkedIn, and Facebook promote short posts that allow sharing of multimedia, such as videos, web page links, and written text. Comments on these posts then create an open conversation, allowing fellow scientists and the public to participate in the conversation.

For example, the *JASA*, *JASA-EL*, and *POMA* accounts of the ASA tweet links to recently published journal articles daily, introducing new work to potential readers. Author participation magnifies the impact of these posts, which can be by either retweeting the ASA tweet with their own message or beginning another a new conversation. Such promotion creates additional opportunities for authors to provide plain language descriptions of their work, overview their methodology, discuss why their research is exciting, and even offer self-critique (Holmes, 2021). Persistence and repetition also play a key role in increasing the wider visibility of publication posts. One recommendation

https://doi.org/10.1121/AT.2022.18.2.79

Figure 1. *The Christmas day "hot chocolate effect" tweet from the Acoustical Society of America (ASA) that had a high amount of engagement between the public and ASA members.*

is to post a link to a recent publication four times in two weeks after publication (Springer Nature, 2022). The ASA accounts practice repetition posting the same article multiple times over a few months. In the authors' experience, each repost of an article generates a larger number of responses.

Promoting Research

Another social media initiative of the ASA promotes popular acoustics articles at relevant times throughout the year. One of the most engaging ASA social media posts from the past year was on Christmas Day 2021 when the Society posted on Twitter a link to a lay-language paper regarding the "hot chocolate effect" from the 143rd ASA meeting (see tinyurl.com/53ypbz94) (**Figure 1**). A few people posted questions about the acoustics described in the paper, and there was a cheerful discussion about it among ASA members.

Finding Answers

In addition to increasing the impact of acoustic publications, social media is a practical way to quickly find answers to specific acoustic questions. Many ASA members are used to searching the articles of the Society publications, but simply asking the acoustic community a question can be faster for when a web search does not turn up a quick answer.

For example, these authors discussed possibly increasing public involvement in acoustics by creating an app that measures and reports on the sound levels of public spaces. We later came across such an app, SoundPrint (see soundprint.co), discussed in ASA YouTube videos and Twitter posts. This shows both the remarkable breadth of acoustic information that exists across the ASA websites and social media accounts and the challenges of finding relevant information. The same information could have been found by asking a question that included the hashtag #acoustics and the ASA with @acousticsorg, which would have the additional effect of revitalizing a past discussion to the interest of a wider audience.

Resources for Specialized Problems

The acoustics Twitter community is active and helpful, making it a good resource for specialized problems. One author was working on an acoustic calculation in a new programming language and tweeted about having difficulty. Another member of the Society sent a script to perform the calculation, which led to the quick identification of syntax errors and a rapid completion of the project.

Similarly, many researchers already use social media to find answers to specialized questions, often visiting question-and-answer forums, such as Stack Exchange (see stackexchange.com) and Reddit (see reddit.com), linked from web searches. These solutions can be both technical and detailed and point to journal articles for complete method descriptions. Reddit already has several active acoustics forums such as r/Acoustics and r/bioacoustics, which feature numerous posts from ASA members that reference ASA publications. Stack Exchange, often more visible in web search results, has a rigorous process for creating specific forums of discussion. The bioacoustics community has recently begun to start a Stack Exchange, the first in acoustics, which will give it a distinct and unified forum for discussion as an alternative to the existing and more general biology, physics, and signal-processing forums. These discussions have the potential to increase the efficiency of designing experiments and processing new experimental data and to enhance the utility of existing publications.

Social Media Usage and Professional Meetings

The use of well-established social media, especially Twitter, is growing in professional meetings, including those of the ASA and the meetings they cosponsor. The organization of social media content, using the same hashtag for a single meeting (#ASA182 for the June 2022 Denver meeting), combines user inputs to help prepare for the meeting, keeps track of topics across concurrent sessions, and monitors the publication of content afterward.

As an example of a premeeting posting to social media, the ASA is encouraging conference authors to make simple, short-looping video overviews (GIFs) of their presentations in the weeks prior to conferences. These GIFs are compiled much closer to the conference than traditional abstracts and allow visual display. The GIF presentation is a simple way to both pique interest of both conference attendees and a public audience. Although often posted to Twitter, the GIF also can be shared on other platforms, such as LinkedIn or Facebook.

During meetings, it is common to see posts about upcoming sessions or special events for the day. These alert attendees about sessions they may have overlooked when reviewing the program. Some attendees will "live-tweet" presentations by providing a short summary of the main points. Reading the brief tweets posted from a session you could not attend allows a person to learn about what they missed. Posts may provide information not included in a title or abstract and may cause a person to reach out to the presenter to learn more.

Finally, social media is an effective way to track the progress of research after a conference. The ASA social media accounts promote both *POMA* articles and popular versions of presentations. The *POMA* account also posts session summary articles, which provide a formatted description of the presentations in special sessions. These posts complement the spontaneity of live-tweet descriptions. Taken together, freely available social media and promoted *POMA* content provide comprehensive and valuable descriptions of the activities of an ASA meeting. This increases their transparency to a larger audience, including members unable to attend.

Social Media Promotion of Outreach and Diversity Initiatives

Diversity initiatives and outreach between researchers and the broader public are important civic and professional responsibilities, and social media can aid their success. Social media facilitates the promotion of events, the sharing of activities, and engages outside members of the public. For example, the twitter account of @AIP_TEAMUP (Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy; see aip.org/diversity-initiatives/team-up-task-force) from the American Institute of Physics has been successful in sharing webinars, employment opportunities, and the successes of African American researchers on social media because Twitter reaches out to undergraduate physics departments across the nation. Similarly, the ASA promotes the Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA) program (see acousticalsociety.org/suriea) on social media for both recruiting underrepresented students and highlighting their projects. This increases the visibility of the program, promotes the success of the participants, and makes it accessible to a wider range of applicants.

For acousticians who are active in scientific outreach, it is essential to communicate on social media platforms that magnify impacts and create a historical record of events. Successful outreach demonstrations often spark interesting discussions and can inspire other researchers and laypeople to engage in hands-on learning. The ASA has an extensive list of activity plans for K-12 students (see exploresound.org). Integrating these activities into science education and sharing them on social media inspires broader interest in this age group. This use of social media avoids reinventing the wheel, facilitates sharing and building on each other's ideas, and amplifies the original lesson content all at the same time.

Conclusion

Although using social media in scientific communities is a new concept, many fields have already demonstrated its potential. The adaptation of social media by the ASA and its members already has created some clear demonstrations of the utility of social media in acoustics, but limited data mean these discussions rely on a personal narrative. A Society-wide demonstration of the utility of social media will require more data generated by more participation. Join up, try it out, and we can explore this new paradigm together.

Note: ASA Publications has recently formed the Engagement Advisory Board to increase the impact of social media postings. The authors of this article are members of that group. Society members interested in participating are invited to email Kat Setzer (katsetzer@acousticalsociety.org).

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Obituary
Reinier Plomp, 1929–2022

Reinier Plomp, professor emeritus of experimental audiology at the Vrije Universiteit Amsterdam, The Netherlands, and Fellow of the Acoustical Society of America, passed away on January 21, 2022. His research interests ranged from basic issues on tone perception to speech recognition in noise by the hearing impaired. *The Journal of the Acoustical Society of America* was his favorite vehicle for publishing his research, with over 50 articles over 40 years.

After graduating from the Department of Physics, Technical University Delft, The Netherlands, in 1953, Reinier joined the Institute for Perception of the Dutch research organization TNO. In his PhD thesis, *Experiments on Tone Perception* (1966), Reinier provided a thorough historical overview of the then-current theories on hearing that were supplemented with new experiments. This included studying the role of frequency resolution in perceiving the pitch of complex tones, as from musical instruments, even after elimination of the fundamental frequency. In a now-classic experiment, Reinier measured the perception of pitch change when applying small frequency changes to individual harmonics of a complex tone. He concluded that the pitch was not determined by the fundamental frequency but essentially by the frequencies of a few lower harmonics. The citation history of Reinier's early publications indicates that these still inspire many colleagues worldwide.

Reinier was strongly motivated by the ideas of the German scientist H. L. F. von Helmholtz in his approach to his research. But Reinier was also impressed by the experimental approach of many American psychoacoustic researchers. In this way, he became a moderator of a transatlantic exchange of ideas in hearing research. In 1969, Reinier organized a meeting, Symposium on Frequency Analysis and Periodicity Detection in Hearing, bringing together researchers from the United States and Europe to discuss psychoacoustical and electrophysiological data on hearing. The proceedings, edited by Plomp and Smoorenburg, were published in 1970. Since then, similar symposia became an international tradition every three years, and they continue even now.

In 1972, Reinier was appointed professor of experimental audiology at the Vrije Universiteit Amsterdam where he focused on the effects of noise on speech communication, especially for the hearing impaired. He developed measuring tools and procedures to quantify the degree of communication handicap resulting from hearing impairment. He also developed a model to describe the effect of noise on speech intelligibility with two main components: *audibility* (or simple attenuation) and *distortion* (loss of the quality of the signal). This approach was followed in the development of the hearing in noise test (HINT) by Sig Soli and still plays an important role in current tests on speech communication.

In a paper focusing on auditory rehabilitation (1988), Reinier took a position against the general trend of applying fast multichannel compression in hearing aids. Thereupon, with several PhD students, Reinier studied the admissible reductions of spectral and temporal modulations in speech without damaging intelligibility as well as the limits of permissible changes in the spectral slope. Based on these studies, he advocated for slow-acting automatic gain control to keep the speech signal within the limited dynamic range of the hearing impaired.

Reinier is survived by his wife Rita.

Selected Publications of Reinier Plomp

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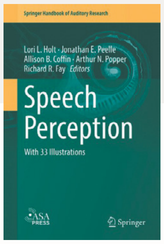
Book Announcement | ASA Press

ASA Press is a meritorious imprint of the Acoustical Society of America in collaboration with Springer International Publishing. All new books that are published with the ASA Press imprint will be announced in *Acoustics Today*. Individuals who have ideas for books should feel free to contact the ASA Publications Office, ASAPublications@acousticalsociety.org, to discuss their ideas.



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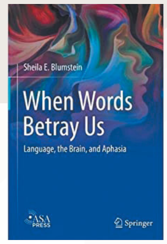

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