JASA ARTICLE

Sounds to Astound: An acoustics outreach show[a]

Jennifer K. Whiting, Mark L. Berardi, Aaron B. Vaughn, Cameron T. Vongsawad,
Tracianne B. Neilsen,[b] Brian E. Anderson, and Kent L. Gee

*Acoustics Research Group, Department of Physics and Astronomy, Brigham Young University, N283 Eyring Science Center,
Provo, Utah 84602, USA*

ABSTRACT:
Sounds to Astound is an acoustics demonstration show, produced for the community twice yearly by the Brigham Young University Student Chapter of the Acoustical Society of America. The free, interactive demonstration show explores the science of sound for a target audience of fifth- to eighth-grade students. Introductory acoustics concepts, such as longitudinal wave motion, wave properties, propagation effects, and standing waves, are taught with live demonstrations, animations, and videos. The goal of this paper is to inspire and encourage readers in their outreach efforts by describing the purposes of Sounds to Astound and technical details of several entertaining and educational demonstrations. Lessons learned from a decade of these student-produced shows serve as an aid for future efforts and highlight the benefits of outreach efforts, particularly for the students involved.

https://doi.org/10.1121/10.0013010

(Received 14 December 2021; revised 9 June 2022; accepted 11 July 2022; published online 2 August 2022)

[Editor: Daniel A Russell] Pages: 835–850

I. INTRODUCTION

Sounds to Astound is an acoustics-specific outreach show hosted by the Student Chapter of the Acoustical Society of America (ASA) at Brigham Young University (BYU). The show is produced by university students under the mentorship of professors. The presenters aim to introduce a general public audience to key acoustic concepts, including longitudinal wave motion, wave properties, propagation effects, and standing waves. The show uses live demonstrations supplemented with videos and animations to engage the audience in physics education. For more than a decade, Sounds to Astound productions have augmented the acoustics outreach efforts at BYU and enriched the education of involved students. These years of learned experience are shared here to facilitate new development of scientific outreach programs.

Scientific outreach programs enhance public awareness and understanding of science. The goal of outreach is to familiarize an audience with both science and scientists (Hendrickson *et al.*, 2020; Andrews *et al.*, 2005). Outreach can take many forms including judging local science fairs, tutoring (Andrews *et al.*, 2005), presenting current research (Clark *et al.*, 2016), and visiting classrooms with demonstrations or learning activities (Crouch *et al.*, 2004; Friedman, 2012; Hendrickson *et al.*, 2020; Laursen *et al.*, 2007). Physics-based demonstration shows are another method of outreach that have been described in the literature (Hendrickson *et al.*, 2020; Price and Finkelstein, 2008; Micklavzina, 2005; McFarland and Kehn, 1996; Taylor, 1996; Leinoff and Swan, 1993; Dennis, 1978). This paper documents an acoustics-specific outreach show.

This live show, titled "Sounds to Astound," is typically produced at BYU twice annually for the local community to promote science awareness, education, and enjoyment. These educational outreach shows are mutually beneficial to all the participants. The audience gains greater understanding of and appreciation for science, including an awareness of ongoing scientific research through multi-modal learning activities and demonstrations (Anderson, 1997; Chahine, 2013; Clark *et al.*, 2016; Jaipal 2010; Waldrip *et al.*, 2010). The student presenters develop teaching, communication, and management skills, learn to promote current research, and obtain intrinsic satisfaction from their outreach involvement (Laursen *et al.*, 2007; Clark *et al.*, 2016).

Sounds to Astound uses a discipline-specific approach to the demonstration show which has distinct advantages. First, the producers and presenters of the show have expertise in acoustics, which typically corresponds with competence in the scientific material and passion in the presentation. Second, a discipline-specific approach allows for a greater depth of scientific exploration that is infeasible for the broad and shallow exploration offered by a more general physics show. Third, acoustics has obvious connections to common experiences, such as speech and music, making the scientific content relatable to the community audience. Last, the acoustics-specific show increases awareness of the breadth and quality of BYU acoustics research.

At the university level, outreach is often viewed as auxiliary to other responsibilities (Andrews *et al.*, 2005). Faculty members with many time constraints may find it

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[a] This paper is part of a special issue on Education in Acoustics.

[b] Electronic mail: tbn@byu.edu

difficult to create outreach content (McCann *et al.*, 2015). When university students step into the role of organizing and presenting the show, professors may act as advisors and consultants. The show successfully engages the audience when the students add their own flair.

Sounds to Astound has evolved over the past decade as different student presenters have participated. Each group of students has brought unique abilities and interests, which have been incorporated into the next iteration of the show. Several students interested in teaching adapted the show based on elements of the K–12 state curriculum to increase the educational value. For example, a "see and hear" pedagogy (Vongsawad *et al.*, 2013; Beauchamp, 2005), interactive engagement (Hake, 1998), and inquiry-based learning activities (Clark *et al.*, 2016) improved the show through integration of evidence-based teaching practices.

All the Sounds to Astound shows aim to excite, entertain, and educate an audience from the local community, while allowing university students to develop oral communication skills. A brief preview of the show from two different years, including interviews with audience members, students, and faculty regarding the science and education involved in the show is available at https://www.youtube.com/watch?v=loDoonqEEMs&ab_channel=BYUWeekly and https://www.youtube.com/watch?v=G15wIZatkPc&ab_channel=BYUWeekly. These videos capture the live audience reaction to some of the demonstrations and highlight the engagement of student presenters and audience members. Many shows are targeted to fifth- to eighth-grade students, but specific shows have been adapted for different audiences, including young children and students with hearing impairments (Vongsawad *et al.*, 2016). Most of the shows strive to raise awareness of hearing loss, a common problem, and introduce current university research to the public.

This paper discusses the Sounds to Astound demonstration show, including the progression of our approach and methods. Technical details are provided for many of the commonly utilized demonstrations. Modifications to the show for unique audiences are described. The impact of the demonstration show is assessed through the value to the student presenters. The paper contains additional resources for readers in designing and presenting their own demonstration shows to educate the general public on key principles relating to acoustics in their everyday lives.

II. DEMONSTRATION SHOW

The baseline demonstration show follows a progression of basic acoustical concepts and gradually introduces more complex ideas. The show typically begins with demonstrations of wave properties and propagation. The concept of resonance and standing waves are demonstrated in multiple formats. The frequency content of complex sounds is then explored with a spectrum analyzer. Demonstrations measuring amplitude (loudness) are incorporated into an explanation of hearing loss prevention, and the audience is instructed on the proper use of earplugs. The show closes with a (literal) bang, as the audience uses their earplugs to safely experience acoustic shock waves from exploding balloons. The following subsections expand on the presentation of the demonstrations used to illustrate each of these concepts; however, more rigorous explanations are available in the referenced literature. Not all presentations are used in every show depending on time constraints or whether the show has a particular emphasis (see examples in Sec. V), but this section provides an overview of the most frequently used demonstrations.

A. Sound is a longitudinal wave

In Sounds to Astound, longitudinal and transverse waves are explored visually and kinetically. One visual representation uses animations of longitudinal and transverse wave motion by animating wave motion through a series of particles. These animations are freely available online (examples at https://acoustics.byu.edu/animations-propagation and https://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html). A physical demonstration of the different wave motions is provided using a long (3 m) slinky. The slinky is stretched across the stage and one end is moved quickly side to side (or up and down) to generate a transverse wave that travels along the length of the slinky. To demonstrate a longitudinal wave, several coils of the slinky are compressed and then released, sending a moving compression wave down the spring. The audience is then invited to create a human-motion transverse wave by having individual audience members sequentially stand and raise their arms. Then, the audience is led to create a longitudinal wave through individual audience members sequentially fist bumping horizontally across their respective rows. In both cases, audience members identified their turn to participate in the wave by seeing the actions of their neighboring audience members.

Singing rods are used to demonstrate that longitudinal waves can travel in solid media (Meiners, 1970; Minnix *et al.*, 1999; Machorro and Samano, 2008; Anderson and Peterson, 2012; Lasby *et al.*, 2014). Aluminum rods with a narrow diameter (generally 1.27 cm or less) and a length of about 2 m work well as singing rods. One key to producing a good sound is to use violin rosin or a sticky powder such as Octadecanol (stearyl alcohol or octadecyl alcohol) on the rod to provide the necessary friction. This friction helps create a stick–slip interaction as one pinches the rod with the thumb and finger of one hand and slides a finger and thumb of the other hand along the length of the rod, as illustrated in Fig. 1. Often multiple finger slides are required to produce an audible tone. Another technique for getting a good sound is to begin the excitation by lightly tapping the end of the rod on the floor or other hard surface to excite resonances before amplifying them with the stick–slip motion. Singing rods typically amaze audiences; they are surprised that such a loud and shrill sound can come from an aluminum rod. Care must be taken to explain that the longitudinal wave is traveling along the length of the bar since there is no visual longitudinal wave motion. A video demonstration is included in the

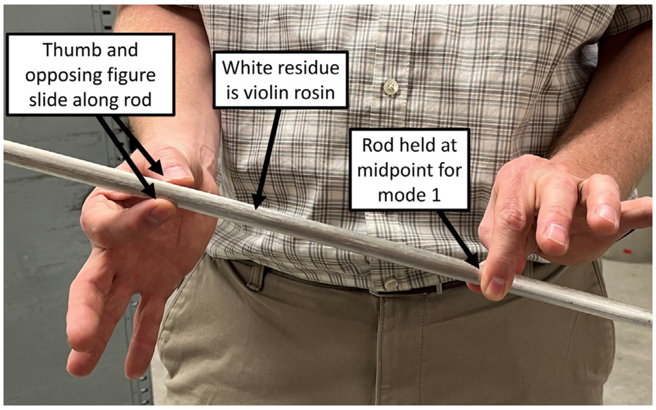


FIG. 1. (Color online) Photograph of a presenter doing the singing rod demonstration. To excite the first mode, the presenter holds the rod at the halfway point along the rod's length (a nodal point) and uses his other hand to grip the rod between his thumb and index finger while sliding the grip along the rod to excite a stick–slip motion and thus longitudinal modes of the rod. Higher modes can best be excited when the rod is held at node points unique to that mode.

supplemental material for this paper (see video demonstration of singing rods in Mm. 1).

Mm. 1. Video demonstration of singing rods. A description of the singing rod used is given along with tips for how to conduct the demonstration. The first four longitudinal modes are excited in a 1.83 m aluminum rod.

B. Sound propagates through a medium

As demonstrated in Sec. II A, waves require a medium to produce vibration. Wave propagation through different materials can be demonstrated with a music box or a vibration loudspeaker. In a mechanical music box, the vibrations of the teeth that are plucked by the pins located on a rotating steel comb, which do not couple well directly with the air to produce large-amplitude sound. However, when the music box is placed on (coupled to) a thin structure (i.e., a soundboard), much higher amplitude sound is produced through more efficient energy transfer to the air. Similarly, a vibration loudspeaker is a specialized loudspeaker for which its coil and magnet are designed to drive a moveable plate instead of the usual cone diaphragm (shown in Fig. 2 and demonstrated in a video at https://youtu.be/rmZbzpWngU4; a copy of the video or an updated link can be obtained by contacting the authors). As a result, the sound radiation is minimal when the vibration loudspeaker is held in the air; however, when placed on a solid surface, the sound is noticeably louder as the vibrating plate causes these surfaces to vibrate, resulting in amplified vibrations in the air that the audience can hear. Examples of vibration loudspeakers may be found at audio-grenade.com or mightydwarf.com. As the vibration loudspeaker is placed on various surfaces around the room (e.g., table, white board, cardboard box, piano sound board), the audience is taught that the loudspeaker is causing these solid surfaces to vibrate. Because the sound can travel in solid media that then radiates into the air, the audience can observe how much sound radiation is achieved by placing the loudspeaker on different surfaces [see Figs. 2(a)–2(c)].

The fact that sound wave propagation requires a physical medium is further emphasized by placing a sound source in a vacuum. This demonstration consists of an alarm placed in a transparent, air-tight container connected to a vacuum pump. The alarm is turned on and continuously plays a sound audible to all in the large auditorium despite the air-tight seal. The air is then pumped out until the alarm is no longer audible. The absence of the alarm sound is particularly noticeable when the noisy vacuum pump is turned off. As the air slowly returns in the vacuum chamber, the audience once again hears the alarm. This removal of the usual medium (air) demonstrates how sound requires a medium to

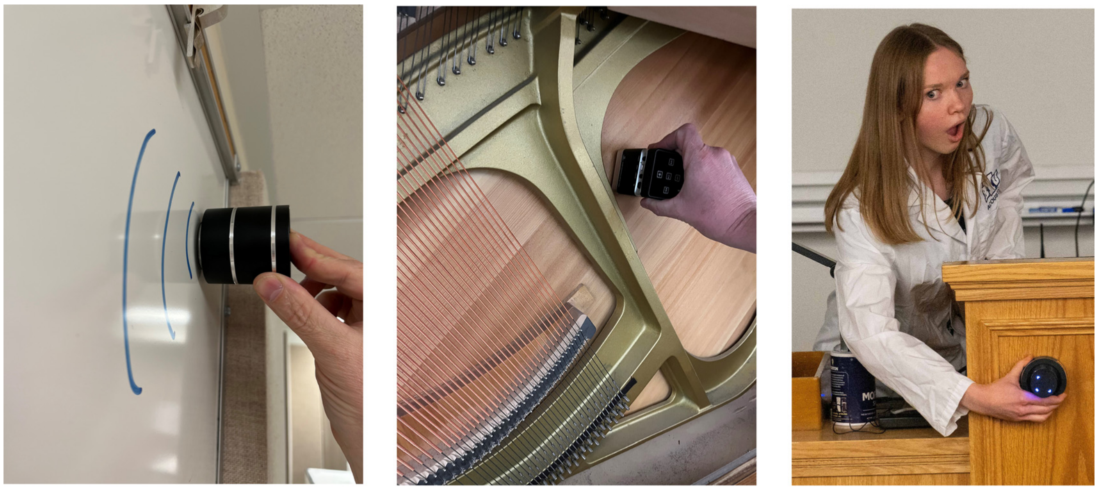

(a) (b) (c)

FIG. 2. (Color online) (a) A vibration loudspeaker placed on a white board. Lines are drawn to illustrate wave radiation into the medium. (b) A vibration loudspeaker placed on the soundboard of a piano. (c) A vibration loudspeaker placed on a wood podium.

propagate [see supplementary material in Neilsen *et al.* (2012) for video 9].

A fun way to reinforce the point that sound wave propagation requires a physical medium is to consider what happens in outer space. An edited video clip of "Star Wars" can be created where sounds during the exterior space scenes are muted but sound during the camera shots from inside the ships remain (see the video at https://youtu.be/F46qfJEjt9w, or contact the authors to get a copy of the video or an updated link). While this clip of "how Star Wars should have sounded" is interesting and entertaining to the audience, similar videos from other sources could be made to demonstrate this phenomenon.

C. Amplitude is related to loudness

The audience is familiar with the loudness of sounds (in the colloquial sense). This perceived loudness can be connected to wave amplitude with several demonstrations. For example, a slinky, rope, or surgical tubing can be used to visually demonstrate the amplitude of waves. The amplitude is connected to the displacement of a vibrating object (displacement means the location of the vibrating object relative to its resting state) and how larger displacements of a vibrating object create larger motion of air and therefore louder sound.

A visual demonstration with mirrors and lasers can also be used to illustrate the connection between wave amplitude and sound loudness. In this Lissajous demonstration, sound from a small loudspeaker causes a mirror to vibrate, and a beam of light from a laser pointer (incident on the mirror) is deflected by the vibrations on the mirror (see Fig. 3). By adding a second loudspeaker behind an additional mirror (the laser beam reflects off both mirrors), the beam is deflected more and produces Lissajous curves from the sparkler's trail effect—a specific application of an optical illusion known as persistence of vision (Nichol, 1857). The setup is shown in Fig. 3, and a video of the demonstration in available at https://youtu.be/2RDJlQlkYkg (or contact the authors to get a copy of the video or an updated link). Increasing the amplitude of the vibrations from the loudspeakers increases sound radiation and the amount of light deflection, thus increasing the pattern size. This visual demonstration of loudness and the size of the light patterns illustrates the relationship between wave amplitude and perceived loudness.

The concept of amplitude and perceived loudness are further demonstrated using sound level meters. Sound level meters are used in audience-participation demonstrations to quantify different sound amplitudes, which the audience recognizes as loudness. For example, subsections of the audience (or individual volunteers) can compete to be the loudest as measured by a sound level meter. Another demonstration can show how the sound amplitude changes with distance from the sound source. Several small sound level meters are distributed to audience members in different locations. Their approximate distances from a sound source are recorded along with the peak levels they measure on the sound level meters. While many people have heard of the term "decibel," they may not be familiar with its definition. "Decibel" is introduced as the unit of sound amplitude while using the sound level meters, and a chart of various typical sounds and their sound pressure levels is shown and discussed.

Exploding gas-filled balloons are an exciting way to demonstrate large sound levels. This demonstration is often used in chemistry classes as a combustion example, but the gas-filled balloons also provide an excellent example of loud noise (Gee *et al.*, 2010; Vernon *et al.*, 2012; Muhlestein *et al.*, 2012). The following considerations are important for a safe demonstration. All participants must be provided with hearing protection. Earmuffs are provided to young children in the audience, and foam ear plugs are distributed to all other participants. The proper way to insert an earplug is demonstrated—rolling it between the thumb and fingers and then pulling the pinna back while inserting the rolled ear plug. After everyone is properly wearing hearing protection, a balloon filled with hydrogen and a balloon filled with a stoichiometric hydrogen–oxygen mixture (obtained from the Chemistry department

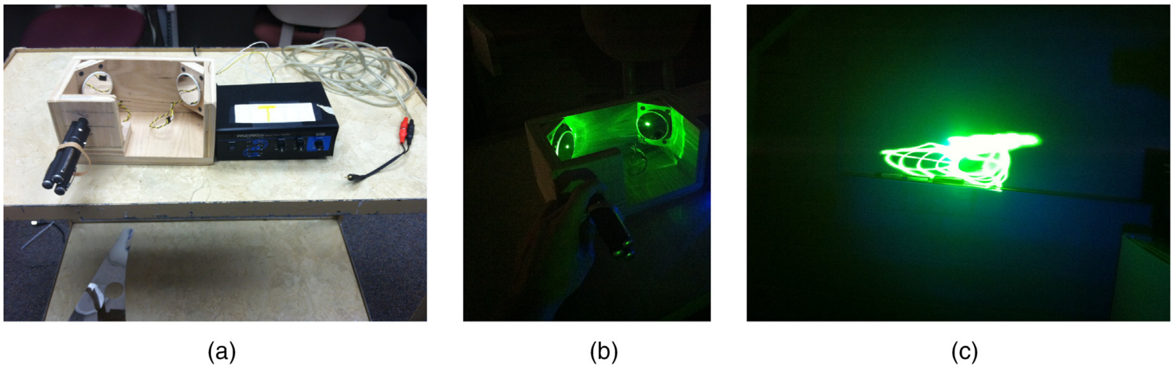

(a) (b) (c)

FIG. 3. (Color online) Laser demonstration uses mirrors attached to small loudspeakers to deflect a beam of light from a laser pointer in order to visually demonstrate the effect of amplitude on beam deflection in a fun visual way. (a) The apparatus with laser pointers mounted to the side of a box and mirrored loudspeakers mounted at 45° angles on two opposite corners of the box. A small amplifier (right) is used to drive the speakers. (b) The beam of light illuminates the demonstration enclosure during a show. A single mirror may be used but only deflects the pattern once, resulting in less complex patterns. (c) The observed pattern caused by deflection due to the vibration of the mirrors on the two loudspeakers.

demonstration area) are each ignited. The exploding balloons are often the last demonstration in the show, providing an exciting conclusion.

D. Frequency is related to pitch

Similar to wave amplitude and loudness, wave frequency and perceived pitch can be connected with several demonstrations. As with the term "decibel," many audience members have heard of the unit "hertz." Often asking the audience how many have heard of "hertz" (and in what context) provides a good introduction to the idea of frequency. Frequency is described as the rate at which the longitudinal sound waves in air are oscillating. The connection of wave frequency to pitch can be shown with the aforementioned Lissajous demonstration described in Sec. II C. A frequency sweep from low to high frequency shows the light pattern from the laser pointer evolving from a large circular shape to smaller, tighter, and more complex shapes, as seen in the video located at https://youtu.be/2RDJlQlkYkg (or contact the authors to get a copy of the video or an updated link). The audience is told that the higher pitch sound is caused by a higher frequency, which results in smaller Lissajous patterns.

A simpler, interactive way to experience frequency uses Boomwhackers®, which are colored, pitched, plastic tubes. These tubes have been used academically to allow students to explore end-pipe corrections (Ruiz, 2014), to teach musical scales and mathematical relationships (Kunish, 2010), and to teach music via aural transmission (Wong, 2016). In Sounds to Astound, these tubes are given to audience members to collectively play familiar melodies. This demonstration can be used as a preshow activity while waiting for the demonstration show to start. To lead the Boomwhackers® choir, a presenter points to colored notes (projected onto a large screen) corresponding to specific tube colors while also announcing the colors. As the audience members strike the corresponding tubes, they play the song. Presenters explain that Boomwhackers® demonstrate the relationship between wavelength and pitch—striking the Boomwhackers® tube creates standing waves in the tube and that the pitch they hear corresponds with a wavelength equal to twice the length of the tube (with both ends open). Audience members see and hear how smaller tubes produce higher pitches (fundamental frequencies) as compared to larger tubes that produce lower pitches. The addition of a cap to one end of a Boomwhackers® causes the tube to sound an octave lower and allows for the discussion on how the end conditions change the frequency of the wave that resonates in the tube.

E. Doppler shift

Once the concept of frequency has been established, the Doppler shift phenomenon is explored. To introduce this idea, a presenter asks the audience to think about times when a perceived frequency changes due to motion, such as the passing of an emergency vehicle. This experience is connected to the Doppler shift, which is then demonstrated with a "Doppler lasso" [see supplementary material in Neilsen *et al.* (2012) for video 7]. This demonstration consists of a speaker playing a constant sine wave at the end of a rope (1000 Hz works well.) As the rope is swung in a circle above the presenter's head, the audience hears the change in frequencies as the speaker moved towards or away from their ears. A video shows that it is irrelevant whether the source of sound or the observer of the sound is moving; a Doppler shift can still be observed (see video Mm. 2). A battery-powered sound source can be placed in the middle of a foam ball that can be thrown around the room to create a Doppler shift as the ball moves towards or away from the audience members.

Mm. 2. Video demonstration of the Doppler shift that occurs when a beeping sound source is playing while a car drives by an observer (the video camera) and then the video camera is placed inside the car as it drives by a stationary observer holding the beeping source. A similar Doppler shift is observed as the car drives by at the same speed in each example.

F. Standing waves

The idea of standing waves, introduced with the Boomwhackers® tubes, is further demonstrated and leads to the concept of resonance. Volunteers from the audience create standing waves on a string (e.g., a jump rope or length of plastic tubing) to illustrate the relationship between wavelength and frequency. Another example is a mounted jigsaw that drives a thin metal belt (Fig. 4) [see supplementary material in Neilsen *et al.* (2012) for video 8]. A similar demonstration can be performed with a length of surgical tubing and a shaker (plus signal generator). One end of the tubing is attached to the shaker and the other is tied to a doorknob

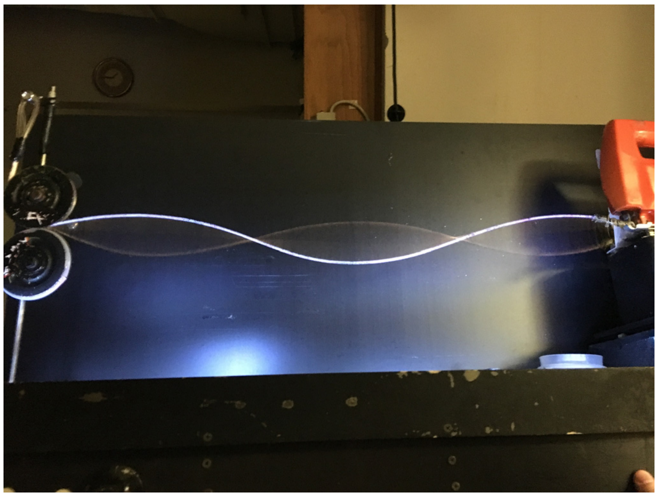


FIG. 4. (Color online) Photograph of a standing wave on the jigsaw demonstration. The jigsaw drives the right end of a thin metal belt up and down at a tunable frequency while the left end is fixed. The third mode is shown. The photo also captures a second fainter image of the string a half cycle later.

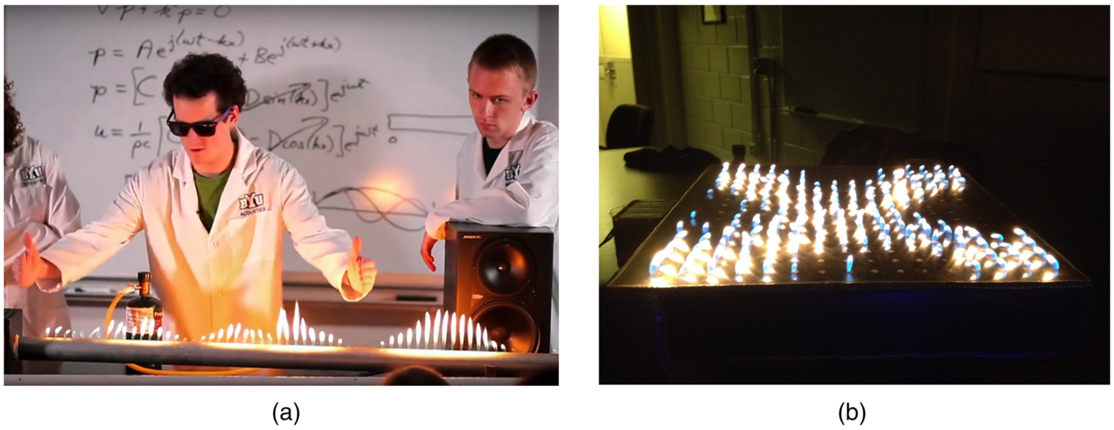
or otherwise secured. Through these demonstrations, the audience observes the standing wave pattern changing with the frequency of the string—specifically the rate at which the string is being moved up and down. In the case of the jigsaw demonstration, the jigsaw frequency is audible, which helps the audience strengthen their understanding of the relationship between wavelength and pitch, since as the jigsaw frequency is increased, the wavelength of the modes decreases. The first and second mode shapes are shown. During the second mode shape, the presenters show that one complete wavelength fits on the string. As higher mode shapes are displayed, the presenter highlights the wave's amplitude, frequency, and wavelength and shows how wavelength and frequency are inversely related. The concepts of nodes (points on the wave with no displacement) and antinodes (points on the wave with maximal displacement) are also introduced. A second part of this demonstration emits a strobe light with a tunable frequency. The presenter can tune the strobe light to the frequency of the standing wave to create a "slow motion" or "freeze time" illusion. For the safety of audience members, always confirm that no audience members have problems with flashing lights (such as light-sensitive epilepsy) before using the strobe light.

Another exciting standing wave demonstration is the Rubens tube. A Rubens tube also creates visual, transverse expressions of standing waves in the gas-filled tube, as shown in Fig. 5 (Rubens and Krigar-Menzel, 1905; Ficken and Stephenson, 1979; Spagna, 1983; Jihui and Wang, 1985; Gee, 2011). The Rubens tube demonstrates standing waves with fire through lighting flammable gas that is injected into a metal pipe and exhausts from small holes along its length (see the Rubens tube in video, Mm. 3). When the gas column is driven at resonance, the time-averaged standing wave behavior inside the pipe is revealed with the height of the flames. Gee (2011) describes different instances where the flame peaks have been observed at pressure nodes (as explained by Ficken and Stephenson, 1979) and at pressure antinodes, when the ratio of acoustic to gas static pressure is sufficiently large. Gardner *et al.* (2009) showed that the holes shift the predicted resonance frequencies to higher values than the standard half-wavelength resonance frequencies that might be expected from the pipe length. The use of a two-dimensional Rubens flame table (Daw, 1987, 1988) has also been explored for the show. With proper safety precautions, the use of fire during demonstration shows is crowd pleasing.

Mm. 3. Video of the Rubens tube in operation with loudspeakers at each end. The tube is filled with propane. The first three modes are shown as frequency is increased. Diagrams of the mode shapes are included.

The concept of standing waves can be extended to two dimensions using a Chladni plate (Stewart and Colwell, 1939; Rossing, 1982; Comer *et al.*, 2004; Worland, 2011). Commonly, a square or circular plate is used, though other shapes can be used, such as a violin body shaped plate (Gough, 2015; Molin *et al.*, 1988; Hutchins, 1981). A shaker drives the plate in its center [Figs. 6(a) and 6(b)] (see video Mm. 4). Alternatively, a violin bow can drive the plate [shown in Figs. 6(c) and 6(d)] [see supplementary material in Neilsen *et al.* (2012) for video 6]. When the plate is driven at a resonant frequency, salt (or sand) scattered across the plate's surface shifts away from antinodes, accumulating along nodal lines. While the plate resonance frequencies can be calculated (Stewart and Colwell, 1939), the plate resonances can be found using a frequency sweep. Modal patterns become more complicated at higher frequencies. Due to the size and orientation of the Chladni plate, a webcam is mounted above the plate and the image is projected onto a screen for better audience visibility.

Mm. 4. Video demonstration of the Chladni plate demonstration. A circular plate and a square plate are driven with a shaker at different resonance frequencies of the plates and salt is sprinkled onto the plates to illustrate the nodal lines of these mode shapes.



(a) (b)

FIG. 5. (Color online) (a) Photograph of a Rubens tube with a fixed end operating in the third mode. (b) Photograph of a Rubens flame table to illustrate two-dimensional mode shapes.

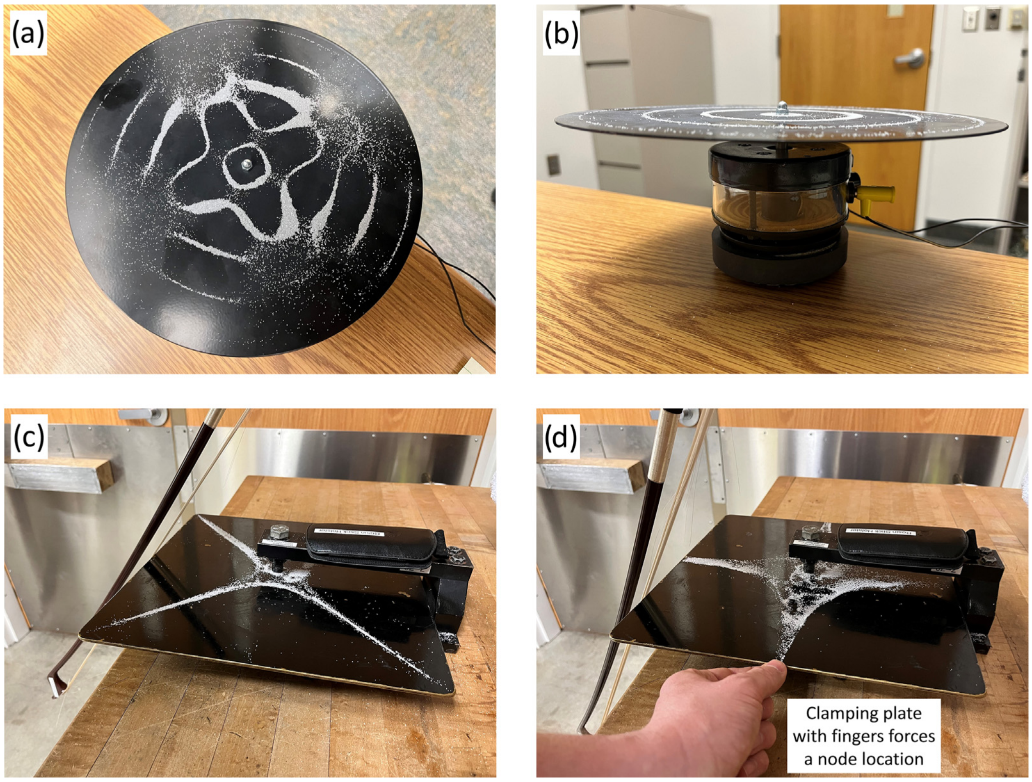


FIG. 6. (Color online) Photographs of a shaker driving a Chladni circular plate (diameter 24.1 cm, thickness 1.3 mm) at (a) 3936 Hz and at (b) 2150 Hz. The shaker is visible in (b). Photographs of a Chladni plate (30.5 cm square, thickness 3.5 mm) are shown while bowed at frequencies of (c) 120 Hz and (d) 75 Hz. In (d) the plate is clamped with fingers to enforce a node location there and change the mode shape. Salt sprinkled on the plate settles along the nodal lines.

Standing waves in three dimensions can be demonstrated using a subwoofer and a function generator in a reverberant space. If the audience has just a few members, they can be asked to find locations in the room where the tone is quieter. For this to be successful, it is advantageous to excite a standing wave that has more than one vertical nodal plane. A room modes tool available at https://amcoustics.com/tools/amroc allows the input of the dimensions of a rectangular room and displays a plot of the various room mode resonance frequencies (Melcher, 2022). When a resonance frequency is selected, a three-dimensional visual representation of the mode is shown, and a sine wave of that frequency is played, which is convenient for a live demonstration. (See supplementary material for a video demonstration showing the second axial mode standing wave in a shower of singing rods with two horizontal nodal planes in Mm. 5).

Mm. 5. Video demonstration of a standing wave in a shower. A loudspeaker plays a 125.5 Hz sine wave while the video camera is moved vertically from the floor to the ceiling. The second axial mode of the shower is excited with two horizonal nodal planes.

Another demonstration of standing waves can be done with a crystal goblet. Flicking the side of the goblet excites a standing wave in which there are four antinodes around the circumference of the goblet vibrating in the horizontal plane (the hoop mode). Alternatively, a wet finger rubbed along the top edge of the goblet provides a stick–slip interaction that excites the goblet at this resonance frequency. Singing at the pitch of the resonance frequency (matching the pitch well) also excites the goblet. A lightweight paper or plastic straw placed inside the glass provides visual feedback as it vibrates back and forth across the goblet while the singer matches the pitch of their singing voice to the resonance frequency. Sometimes the straw vibrates enough to jump out of the goblet. The straw provides visual feedback so the singer can correctly match the pitch of their singing voice to the resonance frequency, and it allows the audience to see that the presenter's singing is causing the goblet to vibrate a lot at its resonance frequency. It is helpful to do this with goblets that have a relatively low resonance frequency so that the pitch is not so hard to reach and sing at loudly. Typically, thinner goblets that are larger in size have a lower resonance frequency. Sometimes if the goblet is weaker or has some flaws in it, the presenter can sing loudly enough to break the goblet. (see supplementary material for video demonstration of a singer breaking a crystal goblet by singing a note that matches the hoop-mode resonance frequency of a goblet in Mm. 6). To help the goblet break more easily, a glass cutter is used to create a small scratch on one side of the goblet. The glass cutter does not need to cut all the way through the goblet; rather, it just provides a flaw that allows the goblet to break more easily. Alternatively, a function generator and a horn loudspeaker can be used to play the resonance frequency loud enough to break the goblet. Care should be taken during this demonstration to protect the presenter with safety glasses and a sufficiently large distance from the audience.

Mm. 6. Video demonstration of a singer breaking a crystal goblet by singing a note that matches the hoop-mode resonance frequency of a goblet. A very small surface scratch was made in the side of the goblet with a glass cutter.

G. Spectral content of sounds

Another way for the audience to visualize frequencies is to use a real-time spectrogram program or app, such as in Buescher (2022). Audience members speak, sing, whistle, clap, etc. near a microphone connected to a real-time spectrum analyzer to observe the frequencies present. A real-time spectrogram reinforces the concepts of amplitude and frequency and can be used to introduce harmonics or speech formants, when that fits with the theme of the show. The spectrogram allows the audience to observe the complex frequency content in speech and other common sounds. A wireless microphone, whose signal is amplified and played back into the room, can be passed through the audience to allow for more participation, though this can become a distraction as some audience members may abuse the use of the microphone.

H. Musical demonstrations

The ideas of complex waves and harmonics can be further demonstrated using musical instruments. The acoustical mechanisms of musical instruments can also be explored. For example, an upright piano with its upper panel removed shows how the hammers strike strings. Different keys on the piano can be played to demonstrate the relationships between string length and density and the perceived pitch of a note. Sometimes less-common instruments are introduced to the audience, such as the Theremin and the hammered dulcimer.

In addition to demonstrations with musical instruments, household objects can be used to make music and the acoustical principles can be explained. Common examples include tuning glasses or bottles by filling them with water, plucking rubber bands stretched over an empty tissue box, and creating a mock brass instrument using a length of garden hose and a funnel. A more ambitious demonstration is building a clarinet from a carrot. (Instructions for the carrot clarinet construction are available from Linsey Pollak at https://www.linseypollak.com/instruments/.).

Musical entertainment is often included in the show. A portion of the show often involves participatory music making with the audience through playing kazoos or Boomwhackers® as described in Sec. II D. Depending on the musical talents of the presenters, demonstrations on musical instruments can be used to illustrate acoustical concepts. Digitally stored musical selections can also be played as part of the laser-mirror demonstration and Rubens tube to both illustrate the complexity of the acoustics in music and to be entertaining. Additionally, synthesizers can drive the Chladni plate and the Rubens tube demonstrations. In these cases, the music played is constructed around the resonances of the plate/tube to create an exciting demonstration.

I. Hearing loss

Most of the shows discuss the importance of preserving hearing ability by avoiding exposure to loud sounds. A decibel level chart illustrates the typical levels of common sounds and emphasizes that levels above 85 dB can cause hearing damage when exposed over long periods of time without protection. Prior to some of the demonstrations, such as the exploding balloons, everyone in the audience is given a pair of ear plugs and is taught how to properly insert them into their ears (as described in Sec. II C).

Excellent examples that simulate the perception of sound by the hearing impaired are available on the "Animated Auditory Demonstrations II: Challenges to Speech Communication and Listening" made by NASA, which is now available online at https://buyquietroadmap.com/334/animated-auditory-demonstrations-ii-challenges-to-speechcommunication-and-music-listening/. The examples include different speech environments (restaurant and factory floor) and different styles of music, with simulated progressively increasing levels of hearing loss. The animations that accompany the auditory examples were created by Nicholas Hawes with support from the NASA Glenn Research Center Imaging Technology Center. This experience of hearing how sound perception changes as hearing ability decreases provides motivation for the audience to actively protect their hearing.

J. Demonstrations of active research projects

When possible, the demonstration show includes references to or demonstrations relating to active research projects. The exploding balloons (see Sec. II C) are one such example (Muhlestein *et al.*, 2012; Vernon *et al.*, 2012, Macedone *et al.*, 2014) that have been used in many research projects (Young *et al.*, 2015; Leete *et al.*, 2015*)*. In addition, the audience is invited to observe our research facilities. Before or after the show, tours of BYU's large anechoic chamber (working dimensions 8.71 × 5.66 × 5.74 m) and reverberation chamber (working dimensions 4.96 × 5.89 × 6.98 m) are offered as part of the educational experience. For maximum effectiveness, the tour groups are restricted to 15 people. The demonstration of active research projects within the BYU acoustics lab spaces provides an opportunity to raise awareness for the research unique to the university. During these tours, undergraduate and graduate student tour guides share brief summaries of current and past experiments, such as exploding gas-filled balloons to

https://doi.org/10.1121/10.0013010

measure shock waves (Vernon *et al.*, 2012). Sometimes, equipment is set up for an experiment, and the audience sees firsthand the more technical side of research in acoustics. For several years, a large microphone array used to capture source directivity (Leishman *et al.*, 2021; Bodon and Leishman, 2015) was in place in the center of the chamber, so the audience could see a direct connection to the experimental setup.

In addition to explaining some of the research, demonstrations in the acoustics chambers afford additional "hear/feel/see" learning experiences. These multi-modal experiences help the audience better understand how the chambers are used for research experiments and reinforce some of the basic acoustical principles presented in the demonstration show. The audience can obtain better awareness and appreciation for scientists generally and acousticians in particular through the connections made with the student–scientist–presenters giving simple demonstrations. This increased awareness is one of the purposes of outreach.

In the anechoic chamber, several demonstrations relate to the directive nature of audible waves. To introduce the anechoic chamber as the "without echo" room, an audience volunteer claps a steady rhythm while the doors slowly shut, fully removing all echoes from the hallway leading to the chamber entrance. After giving a brief explanation of the absorptive materials and shapes used in the anechoic chamber, the presenter invites an audience member to stand in a corner of the chamber and scream loudly while facing towards and away from the rest of the group. Variations of high- and low-pitched screams are encouraged to test the effect and illustrate how high and low frequency sounds are more or less directive.

Directivity of sound waves can also be demonstrated using a parametric array (examples at Holosonic Audio Spotlight, https://www.holosonics.com and https://www.soundlazer.com) that utilizes nonlinear ultrasound to produce a narrow beam of sound in audio range installed near the ceiling of the chamber (Mikulka *et al.*, 2016; Yang *et al.*, 2005). The sound from the parametric array is audible only when directed towards various listeners or redirected with a reflective material, such as a plywood board. The board acts as "an acoustic mirror" to direct the sound towards different listeners. This demonstration opens a discussion on rays and ray tracing used in wave analysis.

The parametric array can also create a bowling ball "loudspeaker." Here, a bowling ball is positioned on a stand below the parametric array, and a miscellaneous cord connected to a patch panel is inserted into one of the finger holes to act as a visual misdirection. Music played through the parametric array sounds like it originates from the bowling ball (due to scattering off the ball). As people do not tend to look at the ceiling when they enter the anechoic chamber, the bowling ball appears to be producing the sound. The presenters lead the audience members in a discussion about how the bowling ball could be a speaker. The discussion also provides an opportunity to discuss how loudspeakers work generally. The explanation of how the sound is being made leads to interesting discussions about how loudspeakers work and provides an introduction to parametric arrays and directional sound sources.

To raise awareness of hearing loss, the audience is invited to sit in the anechoic chamber in the dark for a few minutes. The removal of visual stimuli enables the audience to listen to sounds they are not usually aware of, including breathing, swallowing, and their pulse. Often, an audience member comments on the ringing in their ears, leading to a discussion on tinnitus.

In the reverberation chamber, demonstrations focus on principles of architectural acoustics, especially sound absorption. One demonstration compares the reverberation time of a nearly empty reverberation chamber and one with people. First, a rough impulse response measurement is made with an empty reverberation chamber and a single person. To do this, the person claps and counts the seconds of decay time. These steps are repeated with a full group of people (about 15). The difference in measured decay times is discussed, leading to an understanding that people are absorptive. The experience may also prompt a discussion of concert hall acoustic design, including past research at BYU to assist in the acoustic design of large spaces (Rollins, 2005).

The concept of two-dimensional standing waves can also be experienced in the reverberation chamber, as described in Sec. II F, using a large subwoofer (JBL EON 618S). The large, reflective surfaces in this room make it a particularly effective space for the demonstration of modal patterns in two dimensions. An especially strong visual connection is made when people are asked to stand in locations they think are nodes. The result is a clear modal pattern.

III. PRACTICAL IMPLEMENTATION OF DEMONSTRATION SHOW

We have learned many lessons over the years that help with the practical implementation of Sounds to Astound shows. Some considerations from these lessons include: (1) how and when to advertise, (2) how to manage attendance, such as pre-registration for the show, (3) how many presenters and other helpers are needed to make the show run smoothly, (4) what technical support such as audio-visual is needed, (5) from where the equipment for the demonstrations and technical aspects of the show is obtained, and (6) general logistics for setup and execution of the show. Further details on these considerations are provided in this section.

Depending on the type of show, advertising and registration occur differently. Sometimes, Sounds to Astound is presented as part of Astrofest, a larger event sponsored by the BYU Department of Physics and Astronomy. Other times, the ASA Student Chapter handles the entire production. When producing the show independently, social media is utilized to spread the word, emails are sent to local science teachers and home school groups, and the show is advertised through the local and university news outlets. Because it is difficult to anticipate how many people would attend each show and, thus, plan for the appropriate sized room to reserve, an online reservation form is sometimes used. While the online reservation system is useful, unfortunately, there is a risk of large groups registering and then not attending, leaving empty seats in the audience. Some ideas for counteracting this difficulty are (1) to set a maximum number of seats a single person can reserve, (2) allow 20%–30% more people to reserve spots than can be accommodated in the room, or (3) charge a small fee for each reservation to encourage people to reserve responsibly.

For a typical Sounds to Astound show, six to ten students from BYU's ASA student chapter collaborate to organize and run the show. Three presenters are selected to rotate between demonstrations and keep audience interest. While one presents a demonstration, another assists, and another prepares the next demonstration. Presenters are usually undergraduate or graduate students with a good stage presence who can add some flair and personality to the presentation. For instance, some choose to wear sunglasses while roasting marshmallows over the Ruben tube flames before moving on to explaining how it works (see Fig. 5).

In addition to the show presenters, one to two students act as the technical support team. They control the visual aids (projectors) and auditory aids (presenter microphones when appropriate as well as music and sound for demonstrations) via a laptop and mixing board. The technical team is essential as it allows the presenters to focus on connecting with the audience, performing the demonstrations, and teaching the audience instead of also troubleshooting the technical aspects of the show. Technical crew members are often also trained on the demonstrations in case additional assistance is needed. The presenters and technical crew coordinate with each other following a printed show outline to keep the show flowing smoothly from demonstration to demonstration.

Many student volunteers who do not present in the show also assist in gathering and setting up the demonstrations and ushering the audience. Due to the time required to set up for a show, it is more convenient to schedule several shows in a row (over a weekend, for example) in order to set up and take down the demonstrations only once. However, this is not always feasible if the room used for the demonstration show is required for other uses over the course of show times.

Preparations include collecting demonstrations from various sources, such as the Department's physics demonstration inventory, material used in acoustics courses, and the Chemistry Department demonstration area for the gas-filled balloons. It is a nontrivial matter to move all the equipment to the demonstration room, a lecture hall with capacity for 170, and set the equipment up in a way that decreases clutter and increases the ability to smoothly run the show. For example, about half of the demonstrations should be on opposite sides of the room so preparations for the next demonstrations do not distract from the current demonstration. The location of the demonstrations must also be coordinated for purposes of connecting to the mixing board for the technical crew to run or for other reasons, such as more effective locations in the room to perform the demonstration.

IV. SOUNDS TO ASTOUND EVOLUTION

Sounds to Astound began in 2010, and each year brings new student presenters. The regularly offered presentations vary due to the individual strengths and experiences of the student presenters and intended audience. For each show, the student presenters collaborate to create a "script" or a flow of ideas to best present the acoustical concepts according to the needs of the specific show. A flexible outline format allows the student presenters to modify the presentation of the acoustical concepts in different ways and highlight their personal interests.

Table I shows the usage of various demonstrations in Sounds to Astound over a decade of show production. As the show progressed through the years, student presenters honed in on the demonstrations they preferred to use, whether it was because of a personal preference (excitement is contagious), or because that demonstration most effectively demonstrated the concept being explored in the show. Crowd-pleasing demonstrations like the Rubens Tube and the Exploding Balloons appear in almost every iteration of Sounds to Astound. Other demonstrations do not. For example, the Vortex Cannon (Perry and Gee, 2014) was difficult to operate consistently and successfully. The lighting in the room needed to be precisely configured to see the Vortex Cannon well. This demonstration could also create misconceptions, as it is more of a fluid mechanics demo than an acoustics demo. The Carrot Clarinet is a very fun, surprising, and crowd-pleasing demonstration, but it is also inconsistent, as a new carrot is used each time. While oft used, the real-time spectrogram display (Buescher, 2022) of the signal from a wireless microphone passed around the audience during the show often distracted the audience from the ongoing demonstrations (including children screaming into the microphone), and caused confusion among those who did not understand the purpose. In early iterations of the show, the ripple tank and two interfering loudspeakers provided insightful demonstrations to the interference of waves and phase of acoustic waves. However, later versions of the show did not try to demonstrate wave interference, to allow for time to be spent on different acoustic concepts, so these demonstrations were dropped. Similarly, in some shows, videos demonstrating resonance, such as footage of the Tacoma Narrows Bridge, were shown. In other shows, these videos were not used in favor of live demonstrations of resonance. Over time, the laser demonstration using Lissajous patterns to show changes in sound frequency and amplitude was taken out of use because it was breaking down, and newer students forgot about it, did not know how to use it, or chose to demonstrate the concepts with alternative demonstrations.

Some shows had unique audiences, so the show outline and demonstrations used were tailored to those audiences'

https://doi.org/10.1121/10.0013010

TABLE I. Demonstration usage in Sounds to Astound shows over the years.

	Demonstration	2010	2012	2013, Show 1	2013, Show 2	2014, Show 1	2014, Show 2	2015, Show 1	2015, Show 2	2016, Show 1	2016, Show 2	2017	2018, Show 1	2018, Show 2	2019	2021
Preshow entertainment	Boomwhackers® choir	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sound is a longitudinal wave	Animation			X	X		X	X		X		X	X	X	X	X
	Long slinky, rope	X	X	X				X		X	X	X	X	X	X	X
	Human-motion wave		X	X	X	X	X	X		X	X	X	X	X	X	X
	Ripple tank	X	X	X												
	Parametric array loudspeaker	X														
	Singing rods	X	X													
Interferrence	Two loudspeakers	X	X	X												
	Ripple tank		X													
Sound propagates through a medium	Vibration loudspeaker				X	X	X		X	X	X	X	X		X	X
	Mechanical music box															
	Alarm in a vacuum	X	X		X	X	X	X	X	X	X	X	X	X	X	X
	Vortex canon		X								X					
	How "Star Wars" should have sounded		X		X	X	X	X	X	X	X	X	X	X	X	X
	Long slinky, rope	X	X	X				X		X	X	X	X	X	X	X
Amplitude is related to loudness	Sound level meter	X	X	X	X	X	X	X		X	X	X		X		X
	Long slinky, rope	X	X	X				X		X	X	X	X	X	X	X
	Decibel chart									X		X	X	X	X	X
	Exploding balloons	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Laser Lissajous patterns					X	X	X	X	X		X	X	X		
Frequency is related to pitch	Laser Lissajous patterns					X	X	X	X	X		X	X	X		
	Boomwhackers® and caps	X		X	X	X										
Doppler shift	Doppler lasso										X	X	X	X	X	X
	Doppler rocket							X		X						
Standing waves	Jigsaw and strobelight	X	X	X	X	X	X		X	X	X	X	X	X	X	
	Boomwhackers® and caps	X		X	X	X										

TABLE I. (*Continued*)

	Demonstration	2010	2012	2013, Show 1	2013, Show 2	2014, Show 1	2014, Show 2	2015, Show 1	2015, Show 2	2016, Show 1	2016, Show 2	2017	2018, Show 1	2018, Show 2	2019	2021
	Long slinky, rope	X	X	X				X		X	X	X	X	X	X	X
	Rubens tube	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Chladni plate	X	X					X	X	X	X	X	X	X	X	X
	Crystal goblet	X							X							
Spectral content of sounds	Spectrum analyzer and wireless mic		X		X	X	X		X		X		X	X	X	X
	Video of rocket launch														X	
Musical demonstrations	Upright piano															
	Theremin										X					
	Hammered dulcimer															
	Glass bottles								X							
	Trombone, garden hose, funnel		X						X							
	Carrot clarinet								X							
	Kazoos															
Hearing loss prevention	Proper insertion of ear plugs	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	NASA hearing loss demo	X	X													

https://doi.org/10.1121/10.0013010

interests and needs. In these cases, not all demonstrations listed in Sec. II were utilized.

A. Astrofest

Astrofest is an annual educational outreach event sponsored by the BYU Physics and Astronomy department to share our passion for science with hundreds of people. The BYU Astronomy faculty, staff, and students plan and coordinate this large event, which is held on a Saturday in May. This fun public outreach day is full of planetarium shows, rocket building and launching, telescope use, and tours of the astronomy observation deck. The astronomy outreach team invites participation by the ASA Student Chapter outreach team, the Society of Physics Students outreach team, and the Department of Geology outreach team to accommodate the vast numbers in attendance. Since the event's emphasis is on outer space and astronomy, principles of sound and vibration as they relate to outer space and rocket launches are highlighted, such as the edited "Star Wars" video clip from Sec. II B or ongoing rocket noise research at BYU (Mathews, 2021).

B. Acoustics for the deaf

The Sounds to Astound program was adapted for a group of 80 students between the ages of 13 and 18 yr who are deaf and hard of hearing as described in Vongsawad *et al.* (2016). This experience was designed to reinforce the message that opportunities exist for these students in higher education. Teaching principles of sound and vibration to students who are deaf and hard of hearing was approached carefully. A "See and Feel" pedagogy was employed. Visual demonstrations were used, including the standing wave on a string, the Ruben tube, and the use of a microphone connected to a spectrum analyzer. Demonstrations that focus on feeling vibration are also used. For example, a loudspeaker playing low frequency sound (40 Hz) can blow out a candle. The vibration loudspeaker playing music while placed on a large surface, such as a table or white board, was also popular. The students also visited the reverberation chamber, where a subwoofer operated at the resonance frequencies of the room. The students were invited to walk around the room to experience the stronger and weaker vibrations and identify the nodal lines of the resonances of the room. This experience connected back to the standing wave patterns they had observed with the string demonstration.

C. The sound of science, technology, engineering, arts, and math (STEAM)

Sounds to Astound includes concepts noted in the Utah State Education Core standards (UEN) as noted at https://www.uen.org/core/science/. A workshop for elementary school teachers based on the demonstration show was developed to give the teachers more familiarity with acoustical principles and how to incorporate connections in STEAM, as described in Goates *et al.* (2016). The workshop was an active-learning experience involving hear-and-touch activities to share typical acoustics demonstrations with an emphasis on music. Teachers were provided a kit with objects to do these activities during the workshop along with a lesson plan for incorporating them in class. The activities included waves on slinkies, vibrations on rulers, balloon membrane drums, string and cup instruments, and kazoos.

V. IMPACT OF SOUNDS TO ASTOUND SHOW

In the first decade, the Sounds to Astound demonstration shows have reached more than 4000 people. The yearly documented attendance is shown in Fig. 7. These numbers are accurate to about 10 audience members per show because, during the shows, the presenters were more focused on engaging the audience than counting the number of people in the audience. An online ticketing system for recent shows has helped the student presenters anticipate the

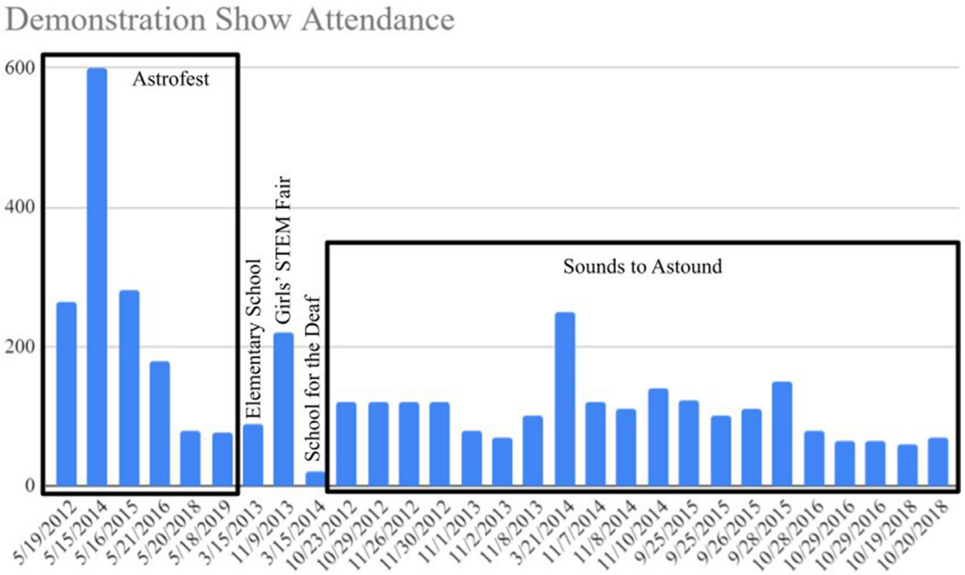


FIG. 7. (Color online) Documented attendance of Sounds to Astound demonstration shows. Specific dates for shows are shown across the horizontal axis. The shows are grouped by type, for instance, Astrofest shows are grouped at the left, and the yearly Acoustics Research Group–produced shows grouped to the right. Specific unique instances are labelled. Fluctuations in attendance by event and by date are evident.

number of registered audience members while preparing for the shows. The fluctuation in attendance across the years was generally related to the success of the advertising efforts. While word of mouth from friends and family brought in the most audience members, advertising through university webpages and social media also raised awareness of the show. Local contacts to the nearby school districts and homeschool groups were also used to advertise.

We have not performed any formal assessment of the show's impact on the audience. However, informal feedback from audience members has suggested they have enjoyed the shows and have appreciated their interactive learning experience. Some families and groups have attended shows in successive years. Many have reported that they found the tours of the anechoic and reverberation chambers to be particularly memorable.

The largest impact of Sounds to Astound over the years has been on the student presenters and participants. A few of these student presenters are shown in Fig. 8, and many more are included in the Acknowledgements. The experience of producing, directing, managing, and presenting has taught valuable skills about teamwork and communication. The presenters have gained confidence from the freedom to modify the show based on individual team members' strengths. This opportunity to unite with other students to provide this public service has been a memorable experience for the student presenters. Multiple student presenters shared that being a part of the Sounds to Astound show was one of the main highlights of their college experience. One presenter stated that thinking about the show reminded them that taking time to inspire and lift others brings a much-needed perspective that keeps you grounded on what is important. A few presenters said that the experience helped them gain confidence in their ability to present and communicate information effectively among many audiences and settings. Many former presenters stated that the experience helped them prepare effectively for various teaching roles and credit the show with their immediate success and confidence as a teacher. Overall, former presenters have reported a positive experience and have noticed many ways in which helping with the show has directly impacted their careers by helping them develop skills such as working with a team, handling logistics, thinking critically, and managing equipment.

(a)

(b)

(c)

FIG. 8. (Color online) Presenters of Sounds to Astound shows. (a) From 2011, (b) from 2015, including some of the authors, (c) from 2021, including a Rubens tube used in the show.

VI. CONCLUSION

The Sounds to Astound demonstration show is a fun and entertaining way to introduce a general public audience to basic acoustical concepts. The ASA Student Chapter at BYU began this show in 2010 and many generations of students have worked together to present these acoustical demonstrations to thousands of people. Over the years, the show has been adapted according to individual presenters' strengths and personalities and to specific audiences. Throughout the show, the acoustical demonstrations vary from simple to more complex, and all add educational and entertainment value to the show. This paper has described these demonstrations and some practical issues involved with hosting the show, hoping to encourage outreach efforts in acoustics. Such outreach events can be adapted based on the resources available and be beneficial to both student participants/presenters and audiences.

Additional resources for demonstrations to teach acoustical concepts with an active learning mindset are plentiful. A selection provided here is suggested as a starting point for finding acoustical demonstrations. The Acoustics Educational Resources database contains educational resources relating to acoustical concepts for a range of educational levels, from elementary school to graduate courses, available at http://tinyurl.com/getAER. Resources for outreach using acoustical examples of physics phenomena in Gee and Neilsen (2014) aim to connect with the general public. Table I in Neilsen *et al.* (2012) lists demonstrations in an undergraduate class with a focus on active learning. Vongsawad *et al.* (2016) describes demonstrations effective for "seeing and feeling" acoustical phenomena for the deaf and hard of hearing. Kits with hands-on activities can be used to effectively demonstrate acoustical phenomena. In addition to the classroom materials kit produced by ASA (Adams *et al.*, 2013), Goates *et al.* (2016) describes a kit of inexpensive materials for elementary school teachers. The authors encourage the perusal of the resources included throughout to spark interest and enthusiasm for acoustics-based outreach.

ACKNOWLEDGEMENTS

Many student volunteers are acknowledged for the hours they spent preparing for and presenting the demonstrations: including but not limited to Adam Christensen, Adam Erickson, Adam Kingsley, Andrew Basham, Benjamin Christensen, Blaine Harker, Caleb Goates, Carla (Butts) Wallace, Chloe Kincaid, Christian Lopez, Corey Dobbs, David Van Komen, Darren Torrie, Eric Whiting, Gabriel Fronk, Grace (McKay) Smith, Ian Bacon, Jared Oliphant, Jay Clift, Jay Eyring, Jazmin (Smith) Myres, Jessica Morgan, Joseph Lawrence, Josh Bodon, Josh Forsyth, Katherine (Hart) Fortney, Kaylyn Terry, Kelli Succo, Kieren (Smith) McCord, Kristi Epps, Kyle Miller, Levi Moats, Logan Mathews, Mark Anderson, Matthew Calton, Matthew Yancey, Nick Ortega, Matea Trevino, Menley (Stewart) Hawkes, Megan Robertson, Michael Bassett, Michael Denison, Michael Mortenson, Michael Rollins, Michael Rose, Mylan Cook, Paige (Simpson) Barker, Paul Russavage, Brigham Ostergaard, Sarah (Shaw) Ostergaard, Sarah (Young) Nelson, Scott Hollingsworth, Spencer Neu, Spencer Perry, Steven Markham, Suzanna Gilbert, Travis Hoyt, Trent Furlong, Tyler Hopkin, Tyler Sanders, and Zach McKenzie. The authors also thank BYU Department of Physics and Astronomy demonstration coordinators, Wayne Peterson and Clark Snelgrove, for their help with demonstrations, the BYU department of Chemistry demonstrations office for the gas-filled balloons, and the organizers of Astrofest: Dr. Jeanette Lawler, Dr. Denise Stephens, and Dr. Eric Hintz for their inclusion of Sounds to Astound. These outreach efforts are supported by the Acoustical Society of America's funding of the BYU student chapter.

Adams, W. K., Clark, A., and Schneider, K. (**2013**). "Classroom materials from the Acoustical Society of America," Phys. Teach **51**(6), 348–350.

Anderson, B. E., Moser, B., and Gee, K. L. (**2011**). "Loudspeaker line array educational demonstration," J. Acoust. Soc. Am. **13**(1), 2394–2400.

Anderson, B. E., and Peterson, W. D. (**2012**). "The song of the singing rod," J. Acoust. Soc. Am. **131**(3), 2435–2443.

Anderson, O. R. (**1997**). "A neurocognitive perspective on current learning theory and science instructional strategies," Sci. Ed. **81**(1), 67–89.

Andrews, E., Weaver, A., Hanley, D., Shamatha, J., and Melton, G. (**2005**). "Scientists and public outreach: Participation, motivations, and impediments," J. Geosci. Educ. **53**(3), 281–293.

Bardasis, A. (**1995**). "Outreach program for middle-school girls," Phys. Teach. **33**(1), 16–17.

Beauchamp, M. S. (**2005**). "See me, hear me, touch me: Multisensory integration in lateral occipital-temporal cortex," Curr. Opin. Neurobiol. **15**(2), 145–153.

Berg, R. E. (**2012**). "Resource letter PhD-2: Physics demonstrations," Am. J. Phys. **80**(3), 181–191.

Bodon, K. J., and Leishman, T. W. (**2015**). "Development, evaluation, and validation of a high-resolution directivity measurement system for live musical instruments," J. Acoust. Soc. Am. **138**(3), 1785.

Boone, W. J., and Roth, M. K. (**1992**). "Organizing school science shows," Phys. Teach. **30**(6), 348–350.

Buescher, Wolf. (**2022**). "DL4YHF's amateur radio software: Audio spectrum analyzer ("Spectrum Lab")," https://www.qsl.net/dl4yhf/spectra1.html (Last viewed April 2022).

Chahine, I. C. (**2013**). "The impact of using multiple modalities on students' acquisition of fractional knowledge: An international study in embodied mathematics across semiotic cultures," J. Math. Behav. **32**(3), 434–449.

Clark, G., Russell, J., Enyeart, P., Gracia, B., Wessel, A., Jarmoskaite, I., Polioudakis, D., Stuart, Y., Gonzalez, T., MacKrell, A., and Rodenbusch, S. (**2016**). "Science education outreach programs that benefit students and scientists," PLoS Biol. **14**(2), e1002368.

Comer, J. R., Shepard, M. J., Henriksen, P. N., and Ramsier, R. D. (**2004**). "Chladni plates revisited," Am. J. Phys. **72**(10), 1345–1346.

Conlon, J. (**2004**). "Physics outreach for WYP," Phys. Teach. **42**(6), 358–362.

Crouch, C., Fagen, A. P., Callen, J. P., and Mazur, E. (**2004**). "Classroom demonstrations: Learning tools or entertainment?," Am. J. Phys. **72**(6), 835–838.

Darvennes, C. M. (**2005**). "Help! There are 60 screaming kids in my lab!—Outreach activities for 5th graders (L)," J. Acoust. Soc. Am. **117**(2), 483–485.

Daw, H. A. (**1987**). "A two-dimensional flame table," Am. J. Phys. **55**(8), 733–737.

Daw, H. A. (**1988**). "The normal mode structure on the two-dimensional flame table," Am. J. Phys. **56**(10), 913–915.

Dennis, J. C. (**1978**). "The Stephen F. Austin traveling science show," Phys. Teach. **16**(1), 11–14.

Dreiner, H. K. (**2008**). "A physics show performed by students for kids: From mechanics to elementary particle physics," Phys. Teach. **46**(6), 358–362.

Ficken, G. W., and Stephenson, F. C. (**1979**). "Rubens flame-tube demonstration," Phys. Teach. **17**(5), 306–310.

Friedman, R. (**2012**). "Exploring the status of science outreach in science teaching," Ph.D. dissertation, University of British Columbia, Vancouver, BC, Canada.

Gardner, M. D., Gee, K. L., and Dix, G. (**2009**). "An investigation of Rubens flame tube resonances," J. Acoust. Soc. Am. **125**(3), 1285–1292.

Gee, K. L. (**2011**). "The Rubens tube," Proc. Mtgs. Acoust. **8**(1), 025003.

Gee, K. L., and Neilsen, T. B. (**2014**). "Resource letter APPO-1: Acoustics for physics pedagogy and outreach," Am. J. Phys. **82**(9), 825–838.

Gee, K. L., Vernon, J. A., and Macedone, J. H. (**2010**). "Auditory risk of exploding hydrogen-oxygen balloons," J. Chem. Educ. **87**(10), 1039–1044.

Goates, C. B., Whiting, J. K., Berardi, M. L., Gee, K. L., and Neilsen, T. B. (**2016**). "The sound of STEAM: Acoustics as the bridge between the arts and STEM," Proc. Mtgs. Acoust **26**(1), 025002.

Gough, C. (**2015**). "Violin plate modes," J. Acoust. Am. **137**(1), 139–153.

Graur, O. (**2018**). "Education and public outreach as an integral part of a scientist's career," Am. J. Phys. **86**(10), 725–726.

Hake, R. R. (**1998**). "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," Am. J. Phys. **66**(1), 64–74.

Harker, B. M., Neilsen, T. B., Gee, K. L., Whiting, J. K., Berardi, M. L., and Calton, M. F. (**2015**). "@BYUAcoustics and @SoundstoAstound: Using social media to enhance research and outreach at Brigham Young University," Proc. Mtgs. Acoust. **23**(1), 025002.

Hendrickson, J. L., Bye, T. K., Cockfield, B. A., Carter, K. R., and Elmer, S. J. (**2020**). "Developing a science outreach program and promoting 'PhUn' all year with rural K–12 students," Adv. Physiol. Educ. **44**(2), 212–216.

Hutchins, C. M. (**1981**). "The acoustics of violin plates," Sci. Am. **245**(4), 170–187.

Jaipal, K. (**2010**). "Meaning making through multiple modalities in a biology classroom: A multimodal semiotics discourse analysis," Sci. Ed. **94**(1), 48–72.

Jihui, D., and Wang, C. T. P. (**1985**). "Demonstration of longitudinal standing waves in a pipe revisited," Am. J. Phys. **53**(11), 1110–1112.

Kunish, A. (**2010**). “Boomwhackers: A public library service for music teachers in the public school system in Oslo, Norway,” Fontes Artis Musicae **57**(3), 291–295, available at https://www.jstor.org/stable/23512150.

Lasby, B., O’Meara, J. M., and Williams, M. (**2014**). “The singing rod (in the modern age),” Phys. Teach. **52**(2), 86–87.

Laursen, S., Liston, C., Thiry, H., and Graf, J. (**2007**). “What good is a scientist in the classroom? Participant outcomes and program design features for a short-duration science outreach intervention in K-12 classrooms,” Life Sci. Educ. **6**(1), 49–64.

Leete, K. M., Gee, K. L., Neilsen, T. B., Young, S. M., Truscott, T. T., and Pendlebury, J. R. (**2015**). “Mach reflections in the propagation of outdoor acoustic shocks generated by exploding balloons,” J. Acoust. Soc. Am. **137**, 2199.

Leinoff, S., and Swan, K. (**1993**). “Catch a wave–A physics outreach program that works,” Phys. Teach. **31**(7), 434–435.

Leishman, T. W., Bellows, S. D., Pincock, C. M., and Whiting, J. K. (**2021**). “High-resolution spherical directivity of live speech from a multiple-capture transfer function method,” J. Acoust. Soc. Am. **149**(3), 1507–1523.

Macedone, J. H., Gee, K. L., and Vernon, J. A. (**2014**). “Managing auditory risk from acoustically impulsive chemical demonstrations,” J. Chem. Educ. **91**(10), 1661–1666.

Machorro, R., and Samano, E. C. (**2008**). “How does it sound? Young interferometry using sound waves,” Phys. Teach. **46**(7), 410–412.

Mathews, L. T., Gee, K. L., and Hart, G. W. (**2021**). “Characterization of Falcon 9 launch vehicle noise from far-field measurements,” J. Acoust. Soc. Am. **150**(1), 620–633.

McCann, B. M., Cramer, C. B., and Taylor, L. G. (**2015**). “Assessing the impact of education and outreach activities on research scientists,” J. High Educ. Outreach Engagem **19**(1), 65–78.

McFarland, E., and Kehn, T. (**1996**). “The fantastic physics fun show,” Phys. Teach. **34**(8), 512–514.

Meiners, H. F. (**1970**). *Physics Demonstration Experiments, Volume I: Mechanics and Wave Motion* (The Ronald Press, New York), p. 496.

Melcher, A. (**2022**). amroc THE Room Mode Calculator, https://amcoustics.com/tools/amroc (Last viewed 25 July 2022).

Micklavzina, S. (**2005**). “Organize your own road show for WYP 2005 and beyond,” Phys. Teach. **43**(4), 212–213.

Mikulka, J., Hladky, D., and Sliz, J. (**2016**). “Parametric array as a source of audible signal,” Prog. Electromagn. Res. 3610–3614.

Minnix, R. B., Carpenter, D. R., and McNairy, W. W. (**1999**). “How to make singing rods scream,” Am. Phys. Soc. Southeastern Sect. Meeting Abstracts **66**, JE–11.

Molin, N. E., Lindgren, L.-E., and Jansson, E. V. (**1988**). “Parameters of violin plates and their influence on the plate modes,” J. Acoust. Soc. Am. **83**(1), 281–291.

Muhlestein, M. B., Gee, K. L., and Macedone, J. H. (**2012**). “Educational demonstrations of a spherically propagating acoustic shock,” J. Acoust. Soc. Am. **131**(3), 2442–2430.

Neilsen, T. B., Strong, W. J., Gee, K. L., Anderson, B. E., Sommerfeldt, S. D., and Leishman, T. W. (**2012**). “Creating an active-learning environment in an introductory acoustics course,” J. Acoust. Soc. Am. **131**(3), 2500–2509.

Nichol, J. P. (**1857**). *A Cyclopædia of the Physical Sciences* (Richard Griffin and Company, London and Glasgow), pp. 571–572.

Perry, S. B., and Gee, K. L. (**2014**). “The acoustically driven vortex cannon,” Phys. Teach. **52**, 146–147.

Price, E., and Finkelstein, N. (**2008**). “Preparing physics graduate students to be educators,” Am. J. Phys. **76**(7), 684–690.

Rollins, S. (**2005**). “The Salt Lake Tabernacle: Acoustic characterization and study of spatial variation,” M.S. thesis, Brigham Young University, Provo, UT.

Rossing, T. D. (**1982**). “Chladni’s law for vibrating plates,” Am. J. Phys. **50**(3), 271–274.

Rubens, H., and Krigar-Menzel, O. (**1905**). “Flammenröhre für akustishe beobachtungen” (“Flame tube for acoustical observations”), Ann. Phys. **322**(6), 149–164.

Ruiz, M. J. (**2014**). “Boomwhackers and end-pipe corrections,” Phys. Teach. **52**(2), 73–75.

Spagna, G. F., Jr. (**1983**). “Rubens flame tube demonstration: A closer look at the flames,” Am. J. Phys. **51**(9), 848–850.

Stewart, J. K., and Colwell, R. C. (**1939**). “The calculation of Chladni patterns,” J. Acoust. Soc. Am. **11**(1), 147–151.

Taylor, D. P. (**1996**). “The physics show,” Phys. Teach. **34**(6), 364.

Vernon, J. A., Gee, K. L., and Macedone, J. H. (**2012**). “Acoustical characterization of exploding hydrogen-oxygen balloons,” J. Acoust. Soc. Am. **131**(3), EL243–EL249.

Vongsawad, C. T., Berardi, M. L., Neilsen, T. B., Gee, K. L., Whiting, J. K., and Lawler, M. J. (**2016**). “Acoustics for the deaf: Can you see me now?,” Phys. Teach. **54**(6), 369–371.

Vongsawad, C. T., Neilsen, T. B., and Gee, K. L. (**2013**). “Development of educational stations for Acoustical Society of America outreach,” Proc. Mtgs. Acoust. **20**(1), 025003.

Waldrip, B., Prain, V., and Carolan, J. (**2010**). “Using multi-modal representations to improve learning in junior secondary science,” Res. Sci. Educ. **40**(1), 65–80.

Wong, G. Y. L. (**2016**). “Transmission and participative structures in the music classroom: A study of a Boomwhackers class in a Singapore institution,” Proc. IMPAC2016 **22**, 128–134.

Worland, R. (**2011**). “Chladni patterns on drumheads: A ‘physics of music’ experiment,” Phys. Teach. **49**(1), 24–27.

Yang, J., Gan, W. S., and Er, M. H. (**2005**). “Acoustic beamforming of a parametric speaker comprising ultrasonic transducers,” Sens. Actuators A. Phys. **125**(1), 91–99.

Young, S. M., Gee, K. L., Neilsen, T. B., and Leete, K. M. (**2015**). “Outdoor measurements of shock-wave propagation from exploding balloons,” J. Acoust. Soc. Am. **137**, 2199.

Zack, R., Vacha, E. F., and Staub, N. L. (**2017**). “Science in action! Outreach program promotes confidence in teaching science,” Am. Biol. Teach. **79**(9), 711–719.