Listening to Waves: Engaging Underrepresented Students Through the Science of Sound and Music

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Music is a central part of adolescent life, and the connections between music, science, and math are vast and deep-rooted in history. In particular, the relationship between sound and the science of waves. This positions musical sound as an ideal avenue for students to explore and connect with science. Listening to Waves (LTW) is a program that introduces adolescents to the physics and technology of music and sound with the goal of improving their attitudes toward science. For this, LTW creates web-applications designed to explore and create sound in a playful manner and integrates those applications with hands-on exploration of the physical sonic world.

In the case-study described below, LTW partnered with a large middle school serving low-income and underrepresented students, trained the teachers to use the web applications and associated activities, and worked directly with eight-grade student-participants. Students enjoyed the program and participated enthusiastically. Pre-post surveys indicate that program participation improved the students' attitudes toward science, including their intention to pursue a science career and their perception of themselves as capable of doing science.

LTW's web-applications and associated curriculum (Minces 2021) are free and publicly available, and they are starting to be implemented independently by teachers, thus, this program holds the potential to improve the educational experiences and science-attitudes of a large number of students.

METHODS

Program Implementation. The activities and data reported here correspond to a case study involving 350 eighth-grade students at a large urban middle school near the United States–Mexico border (87% Latinx, 8% African American, 47.5% English Learners, 91.5% low SES). The program included three two-hour sessions delivered over one month, with students working in groups of three, and was incorporated into the eighth-grade science curriculum, in which students learn about waves. Before starting, LTW's personnel met several times with teachers, guiding them through the online tools and associated lessons created by LTW, answering questions about the physics of sound, and providing basic training so they could assist during activities carried out by LTW's team and eventually implement them independently. Each session was designed toward experiences of surprise and beauty inspired by observations in previous rounds of study. The experiences can be seen in video 1 (Although the video represents a slightly older experience than the one described below, it was filmed in the same school, and the activities largely overlap.).

The sequence of activities is as follows:

(*1)* *Signal generator.* Led by teachers, students are introduced to the phenomenon of sound as a vibration. For this, they start by touching their throats and vocalizing, thus recognizing the vibration of their vocal cords. Further, students use the signal generator tool (video 2) to create sounds and visualize their waveforms, independently controlling frequency and amplitude. Students discuss how an electronic signal created by a computer is sent to the speaker, making it vibrate and creating sound. This facilitated discussion of sound as vibrations and related the pitch of a sound to the frequency of the vibration and loudness to amplitude. Students further build on this knowledge by using the signal generator to measure each other's frequency threshold (the highest frequency heard), and are greatly surprised to find out that they can hear frequencies that their teachers cannot. Students also use the tool to compare pure tones with complex tones and explore the musical concept of timbre.

(*2)* *Sound engineering.* Dr. Minces starts this class by asking students to listen attentively to a piece of electronic music by *Infected Mushroom*, which features very rich and unusual sounds. This is followed by a discussion of how the art of electronic music uses computers to carefully design electronic signals to be sent to a speaker, which relates to prior experience with the signal generator. Next, Dr. Minces guides students to edit sound. Students can, for example, record themselves and change the timescale to see the waveform of their voices and compare them with those produced with the signal generator. Students also can create rhythms by looping the sounds they record, which often produces sound effects that students find surprising. Dr. Minces discusses how looping and resampling songs is at the historical origins of hip hop, relating waveforms and technology with students' musical awareness. Further, students record and transform sounds through various sound effects and layering, creating a sound composition as a final product. All these operations can be performed with LTW's *oscilloscope* application (insert video 3).

(*3)* *Object vibrations lab.* This lab starts with Dr. Minces holding a metal pipe and striking it with a mallet, which produces a beautiful, sustained sound that draws students' attention. Then Dr. Minces gives the pipe and mallet to a student, but when the student hits the pipe, the sound is a "thunk." This typically greatly surprises students and makes them giggle. The "thunk" occurs because, for an object to vibrate freely, it needs to be held at certain points called vibrational nodes, which students learn throughout the session. Students alternate exploring how pipes vibrate through a sequence of activities and collective discussion. They also compare the sounds of short and long pipes that make a high and low pitch respectively. Ensuing discussions help them build on their knowledge of the relationship between frequency and pitch (experienced in module 1) to discern which pipes vibrate faster. Finally, the class uses the oscilloscope tool to visualize the pipes' soundwaves, which are very pure. This connects the experience of the signal generator, the oscilloscope web application, and the exploration of the pipes' vibrations.

(*4)* *Sound circus.* Dr. Minces starts by demonstrating several unusual and surprising sound-making objects, some of which are musical instruments, such as the *musical saw*, the Brazilian cuica, or the theremin. Others are recontextualized everyday objects, such as bolts of different sizes (that produce a melody as they are thrown on the ground), a slinky (if one touches their ear to the slinky and lets it hang it sounds like a laser gun from *Star Wars*), or a 100-meter sewage pipe (the pipe transmits sound with little loss of volume). The workshop builds on students' newly acquired knowledge of vibrations, discusses the physics of the sound-making objects (what is vibrating and how fast), and situates objects in their cultural context (e.g., explaining the role of the theremin within the history of electronic music). Students are then invited to play freely with the objects.

(*5) Musical Spectrogram.* Guided by their teachers, students use the online spectrogram tool to analyze sounds (video 4) and to explore common sound effects (signal processing) and musical scales, further choosing a five-note musical scale to use in the next module. This activity relates the concept of frequency with the musical concept of musical scales.

(*6) Instrument building.* Guided by Minces, this final activity integrates the previous experiences and knowledge to create a culturally relevant product: a musical instrument. Students receive long metal pipes and pipe cutters, and learn how to use them. Students also receive a written table connecting frequencies and pipe lengths, so they can calculate the lengths corresponding to the frequencies they chose in module 5. After students cut the pipes, Dr. Minces provides boards, nails, and rubber bands for students to mount the pipes, ensuring that they are held at the vibrational nodes so they make a sustained sound. Further, students use the spectrogram to verify the frequency of the pipes.

(*7) Wavemakers.* Guided by their teachers, students watch the docuseries (video 5)

Data collected. Data collection for this case study included observation of students and field notes, video and audio recordings of student group interactions, and pre- and post-surveys. Here, we focus primarily on results from surveys, though interpretations of this data are also informed by observations, field notes, and video analysis. We collected pre- and post-surveys from 88 of 350 students (25%) who submitted the necessary forms as approved by The University of California, San Diego, Human Research Protection Program. The survey included items that have been used widely in measuring engagement and attitudes. The items were taken verbatim or lightly adapted by LTW's evaluator Policy Studies Associates from their Youth Engagement, Attitudes, and Knowledge (YEAK) Survey, which was used in the National Assessment of Educational Progress surveys administered to nationwide samples by the National Center for Education Statistics (Mielke 2012). Surveys were administered within a week before and after the program took place. Each item had four possible responses: Strongly Disagree, Disagree, Agree, Strongly Agree. Statistical significance was assessed with a Wilcoxon signed-rank (non-parametric) test. In the post surveys we included the questions: *"Do you think your school should have this program as part of eighth-grade science next year?"* followed by *"Why do you think so?"*

RESULTS

Survey results. Pre- vs. post- surveys indicate that participating in the program improved the students' attitudes toward science (Table 1).

Satisfaction with the program. After participation, 99% of students agreed or strongly agreed that the program should be implemented in the following years. When asked to write a sentence describing why, 73% used words connoting positive emotions such as *fun, cool,* or *excited*, and 62% used words connoting intellectual engagement such as *curious, interesting,* or *learn*. The two categories frequently overlapped; for example, a student answered: *"I agree because it's such a great experience and lots of fun. I wasn't very into science at first but now I really like it and find it more interesting."*

Student achievements and engagement. All groups of students finished their sound compositions, including many layers of sound and signal transformations, found nodes on the pipes, chose musical scales with the spectrogram, and successfully built their musical instrument. The students participated in the modules playfully and attentively, exploring and sharing their "discoveries" with their peers, very often using expressions of wonder. For example, after they explored how pipes vibrate, we visualized their sound using the oscilloscope tool. When the students saw the waveform appear on the screen, many of them yelled "Ooohhhh!" Such expressions of wonder were repeated frequently throughout the program. Students often related the activities to everyday encounters with sound. Students also appeared to value the musical instrument they created, as they often argued to see who in the working group would take the instrument home, and teachers reported that they kept playing with the instrument during breaks throughout the day.

DISCUSSION

The survey results indicate that program participation improves students' attitudes toward science in several ways. Students indicated that they were considerably more engaged in the science of sound activities than in a generic science activity (question A) or in their typical science classes (question E). Significantly, they were much more likely to agree or strongly agree that while the science of sound was taking place (E-post), science was one of their favorite subjects (71%), their preference for science at other times (E-pre) was much lower (42%). It is remarkable that for so many students the science class becomes a favorite. Assuming that the students' appreciation for non-science subjects did not decline during this period, this dramatic change indicates that the students' overall appreciation of classes—and therefore their daily school experience—increased. Further, the effect goes beyond the specific time spent in the program, extending into students' science self-efficacy (question C) and students' intentions to pursue a science career (question B).

The program design intentionally builds on prior knowledge across modules. For example, the experience with the *signal generator* allows the students to arrive at the *object vibrations lab* with an understanding of the relationship between frequency and pitch, which allows them to reflect that longer pipes vibrate slower than shorter pipes (because they have a lower pitch).

LTW contains several design features organized to respond to challenges of underrepresentation in science learning pathways and careers among students and families contending with low-income circumstances and marginalization along lines of racial/ethnic heritage, immigrant, and refugee positions/status. Focusing on musical sound allows the program to build on the students' experiences and abundant *strengths* and incorporate several dimensions that foster equity and diversity in STEM education, as identified in the *Framework for K–12 Science Education* (National Research Council 2012). LTW targets those dimensions in that it

(1) Approaches science learning as a cultural accomplishment, in the sense that participation allows science and science understanding to grow out of the students' lived experiences of sound and music.

(2) Builds on prior interest and identity, where the prior interest is in music, and the identity relates to their music interests, which they often re-engage as they record and transform their favorite songs or their voices. Nearly all (95%) of LTW students strongly agreed with the statement "I like music."

(3) Connects science with students' cultural funds of knowledge as they relate to music. Students were persistently invited to draw on their lived experiences, peer and family experiences of sharing music and sound, and social worlds for generating playful and logical inquiry practices. These links were supportive when visualizing and manipulating sound waves (creating loops, changing the speed) to construct scientific understanding.

(4) Makes diversity visible, by connecting the subjects that the students are learning with the science and life experiences of underrepresented near peers, through the *Wavemakers* docuseries that explored lived experiences of featured young scientists.

(5) *Values multiple forms of expression,* in the sense that students can express their understanding not by taking tests, but by the products they create, such as the sound compositions and musical instruments.

CONCLUSIONS

Whereas the potential for integrating music and science has been recognized (Emdin 2010), few have studied the issue quantitatively (Freeman et al. 2014), particularly as it relates to underrepresented students. Furthermore, many experiences have focused on students participating in out-of-school, after-school, or elective classes, which often attract students that already have an interest in the subject matter. The results presented here indicate that music-science integration can be a powerful tool for engaging underrepresented students in their own classrooms, thereby reaching all students, including those who may have poor attitudes toward science. LTW's web applications provide students and teachers easy access to engaging tools that were once rare and expensive. That ease of accessibility makes some of these activities highly scalable. To facilitate this scaling and the use of the online tools, LTW collaborated with the San Diego County Office of Education (SDCOE) to create an associated curriculum aligned with the science standards, focusing on the core idea of waves (PS4) and including various crosscutting concepts and science and engineering practices, see https://listeningtowaves.com/lesson-plans. The curriculum builds on activities 1 and 2, and embeds them into a larger learning sequence that requires only materials available online. The collaboration followed a teacher action research model, in which *teacher-leaders*—practicing teachers who are experts in curriculum development—work with subject-domain experts to create relevant learning modules; they implement those modules in their classrooms and meet again with the subject-domain experts to discuss the results and iterate the learning modules accordingly.

Since the creation of the curriculum, LTW has been working with teachers, training them on the use of the online tools and the basics of the physics of waves and sound, and has trained more than 100 teachers throughout the country via teleconference, in professional development sessions ranging from 2 to 15 hours. The tools and curriculum have been accessed more than 80,000 times this year to date. A future direction of LTW is to further develop this scale-up model, to work with SDCOE to add learning modules based on the activities described above, and to evaluate the effectivity of the professional development and the teacher-led implementations. We suggest that future research, by this and other groups, should focus on understanding how music-integrated STEM programs can be designed for broad reach and accessibility.

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The materials described above, as well as lesson plans associated with the web applications, can be accessed freely here. The reader is welcome and encouraged to reach LTW, through its website, for suggestions, questions, and free training opportunities. This work was supported by NSF Innovative Technology Experiences for Students and Teachers (ITEST) id 1657366. Connecting STEM to Music and the Physics of Sound Waves. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Survey results. Pre- vs. post-surveys indicate that participating in the program improved the students' attitudes toward science (Table 1).

Survey item	SD	D	A	SA	P-Value
A. Pre. "I usually get excited when I find out I will do a science activity."	0.07	0.28	0.44	0.2	
A. Post. "I got excited during the science of sound."	0.02	0.09	0.47	0.42	**P < 0.0001**
B. Pre. "When I graduate from high school, I might like to have a job related to science or engineering."	0.2	0.33	0.36	0.1	
B. Post. "When I graduate from high school, I might like to have a job related to science or engineering."	0.1	0.39	0.31	0.19	**P < 0.02**
C. Pre. "I am good at science."	0.11	0.37	0.36	0.15	
C. Post. "I am good at science."	0.06	0.28	0.55	0.11	**P < 0.016**
D. Pre. "Science is boring."	0.18	0.48	0.22	0.11	
D. Post. "Science is boring."	0.26	0.49	0.2	0.05	**P < 0.03**
E. Pre. "Science is one of my favorite subjects."	0.2	0.36	0.3	0.12	
E. Post. "Science was one of my favorite subjects in the last weeks."	0.06	0.22	0.47	0.24	**P < 0.0001**

Table 1. LTW inclusion in science class improves students' attitudes toward science. Values represent the proportion of students in each category: strongly disagree (SD), disagree (D), agree (A), strongly agree (SA). Column 1 indicates the survey item. White rows indicate results before (Pre) and blue rows after (Post) participating in LTW. Significance was calculated using a Wilcoxon signed-rank test. Students reported they were more excited by our program than by a generic science activity (A), had increased intention to follow a STEM path (B), had increased self-efficacy (C), were less likely to think that science is boring (D), and showed increased engagement with science classes for the duration of the program (E).

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