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LISTENING TO WAVES: USING COMPUTER TOOLS TO LEARN SCIENCE THROUGH MAKING MUSIC

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Abstract

The present paper details our experience launching an outreach project across several schools in the greater San Diego Area. Our program leverages the deep interest that society has in music to engage students in learning the basics of signal processing and the science of waves and vibration. Our program provides a hands-on and creative learning experience. We describe various aspects of our curriculum, including approaches for incorporating lessons within regular school activities.

In recent years, the integration of arts as a means of teaching subjects in STEM fields (STEAM=STEM+ART) has gathered traction. Often STEAM takes the form of doing art about science. Such an approach can be very useful since art is able to convey and portray scientific concepts with great clarity and thus might prove fundamental for a deep understanding of scientific concepts. However, this approach also risks establishing a division between science as a message and art as a carrier. For those of us who have explored the paths of both art and science, this hard division does not exist. We do science because we find beauty in it, a beauty that we can explore and “bring out” just as much as we do when we are painting or playing music. We also understand that there is science in art, and we need experimentation, research, and a deep understanding of our artistic media, to create beauty or transmit a message. This is well exemplified in the making of music and in particular in the making of sounds, since sound is created through vibrating materials and composed of waves.

In our educational program the students learn the hidden and ubiquitous world of waves through the making and analysis of music and sound. For this, they use computer tools to record, visualize, manipulate, and create sounds, thus learning the basics of wave theory and signal processing. Integrating science and arts, the students design creative musical instruments or sound installations and analyze their acoustic properties. They explore how sound is propagated through the environment and represented in the brain. At the end of this program the installations created by the students are presented in a public art-science-show. In this way, the entire community can appreciate the richness of the physical world embedded in music. Our goal is that, through this program, the community will not only learn about vibrations and music, but also will also understand that the laws of nature are not restricted to outer space or micro-organisms but pervade all that we know and love.

1 MUSIC AND SCIENCE

Music and science have long been integral parts of traditional western education, linked since the very origins of mathematical thought, and the connections that can be formed between the two fields are nearly endless. Music is an interest and activity that transcends ethnic, economic, and social boundaries and serves as a marker of sociocultural identity. Nearly everyone is strongly engaged by one type of music or another and, through constant exposure, is already highly expert in perceiving fine details of musical sound. Building a connection between science and sound does not only affect the way in which students perceive science, but also the way in which students hear and experience the world, thus enriching their everyday lives. With this in mind our team, led by researchers in the cognitive science of music, from the University of California in San Diego, is devoted to transmitting our knowledge and interest in sound, art, and science through the creation of Listening to Waves (LTW), an educational program at the intersection of these fields.

We have currently applied our program to 180 students and worked extensively with the teachers to integrate our school visits with their class activities, in this paper we describe our experience, focusing on our initial program in High Tech High School North County, in San Marcos, California (HTHNC). In order to convey the full motivation for our program as well as the development and launch process, we first provide an overarching description of the program's philosophy and goals. We follow with descriptions of example lessons created by cognitive science researchers with physics and ethnomusicology backgrounds, respectively (Drs. Minces and Khalil), and by the classroom teacher (Dr. Challen) with a background in Biotechnology and in Science Education. Finally, we describe our observations of the students' responses to the activities they performed, and we reflect on the interaction between active scientists and school teachers.

2 LTW OUTREACH PROGRAM

From quantum physics to gravitation, from the micro to the macro scale, waves are pervasive in the physical world. A deep knowledge of the behavior of waves is not only fundamental to the physical sciences, but is also necessary for understanding diverse concepts in many fields such as chemistry, neurobiology, or geology, electronic and structural engineering. Moreover, understanding waves is a key element of understanding signal processing and is thus an important component of career preparedness for the information and communications technology (ICT) workplace and the entertainment industry. *Listening to Waves* seeks to build a connection between a physical phenomenon that is ubiquitous in our everyday lives (sound), the physics behind this phenomenon (waves), and applications of this knowledge that might be conducive to careers in STEM.

The pervasiveness of sound, its ease of measurement, and its cultural relevance reveals the sonic world as a "natural laboratory" through which adolescents may become intuitively familiar with waves and their properties. From speech, to music, to street noise, sound is an integral part of our everyday lives. It is easy to measure: one only needs a microphone and a computer. People are intuitively familiar with many aspects of sound waves and their perceptual signatures such as pitch, timbre, loudness, direction, and echo. People are also familiar with many objects that generate sound (vocal chords, flutes, drums, strings). Sound is the material from which music is made; creating sounds constitutes a large portion of music-making. A love for music and the playing of musical instruments permeates all cultures and socio-economic strata and is part of everyday life throughout the world.

2.1 Course description

The length of the program varies according to the venue and the availability of the school, outlines of lesson plans can be seen on our website: "http://www.listeningtowaves.com". Classes are taught by the creators of *Listening to Waves*, computational neurobiologist Dr. Victor Minces, native Spanish speaker, and cognitive scientist and ethnomusicologist Dr. Alexander Khalil. In the experience reported here Minces and Khalil led some of the activities, other activities were led by classroom teacher, biotechnologist, and science educator Dr. Cate Challen.

Through participation in this program students learn the hidden and ubiquitous world of waves as they make and analyze musical sound. To accomplish this they create waves and vibrations in physical objects (building their own unconventional instruments), use computers to analyze their waveforms and acoustic properties, and explore how sound is propagated through the environment and represented in the brain. In addition to the activities carried out with the instructors, we engage adult volunteers from academia and industry who specialize in extended use of wave theory to explain the role of waves in their respective fields, thereby emphasizing the linkage between STEM domains. This further promotes STEM and ICT career awareness using waves, a subject the students already have experience with, as a common denominator. The lesson plan is designed as a series of experimental activities that integrate creativity with critical thinking and signal analysis technology. At the end of this program, the participants create experimental musical instruments that are presented as installations in a public art-science-show. In this way the understanding of waves through sound extends beyond the participants to their broader communities, and the students become teachers.

2.2 Learning goals

A primary learning goal is for our students to understand the nature of sound: how objects vibrate, and how these vibrations are propagated in space. We intend for students to develop intuitive notions of frequency decompositions of sound (as represented in a Fourier transform). By the end of this program, participants should be able to connect a sound they hear, the characteristics of the object that created it, its waveform, and its spectrogram. They should also understand that the wave knowledge they have acquired applies to various domains other than sound.

2.3 Engaging in STE[+a]M

Student-centered learning methods, based on the work of Piaget [1] and Vygotsky [2], have been recognized as promoting active learning by engaging students during classroom exercises [3]. Student engagement has been broken into four factors: behavioral, emotional, cognitive, and agentic. Behavioral engagement is defined as teachers directing students into activities that require them to apply initiative [4]. Emotional engagement is defined by stimulating students into interaction with the subject matter [5]. Cognitive engagement is defined as the teachers asking questions so that students elaborate on ideas covered [6]. Agentic engagement is defined as self-learning by the student with instructional support from the teacher [7].

According to a research report from the National Endowment for the Arts [8]regarding the academic achievement of students that participate in the arts, “At-risk teenagers or young adults with a history of intensive arts experiences show achievement levels closer to, and in some cases exceeding, the levels shown by the general population studied” suggesting that “in-school or extracurricular programs offering deep arts involvement may help to narrow the gap in achievement levels among youth”. It is not clear, however, how the creativity and capacities of these high achievers can be funneled into a career in STEM. The STE[+a]M education movement, adding the arts to STEM education, has been gaining traction in recent years, as evidenced by the creation of a congressional STE[+a]M caucus (http://stemtosteam.org/events/congressional-steam-caucus/). A subjacent concept in STE[+a]M education is that the engagement that students have in the arts can be transferred to science. However, the integration of art and science is not always smooth, taking the form of *balancing* art with science or simply making art that represents science. The role that art can play as an engagement tool for STEM education has yet to be thoroughly investigated.

Our program uses sound and music as the engager because of its particularly personal and social features. Although music is not a “universal language”, as understanding a given type of music can only be achieved through cultural knowledge and repeated exposure, it is universal in that all known cultures worldwide and throughout history have produced music of some kind [9]. Adolescents have a strong tendency to be especially engaged with music as it relates to developing a sense of individual and cultural identities and interpersonal relationships [10]. More importantly, while the sounds of different genres and styles of music might be extremely varied, they are equally available to study through the physics of waves. This allows students to engage with physics through whatever type of music is most relevant to them. Moreover, the populations that have been found to disengage or be discouraged from pursuing STEM during adolescence [11], [12] do not demonstrate disengagement with music [13]. This universal interest in music amongst adolescents not only suggests high retention rates for the Listening to Waves program but also suggests that this program holds significant potential for engaging adolescents from populations that are typically underrepresented in STEM and holds the potential to draw them into STEM studies and careers in the future. It also will serve as a gateway program for additional STEM learning and engagement with technology both in making music and in learning STEM.

3 ACTIVITIES

3.1 Seeing sound

The goal of these activities is to acquaint students with the most important properties of sound: sound as composed of different frequencies (frequency decomposition), and sound as a traveling wave of pressure in the air (waveform).

3.1.1 Frequency decomposition

The goal of this section is to generate an intuitive understanding of spectrograms. Our main tool is Ultima-Sound, free software for Windows that generates spectrograms in real time. The lesson proceeded as follows: Several computers were set up with the software running prior to the students entering the classroom. When they entered, they found the spectrograms running and they naturally started to experiment by making noises and vocal sounds into them. Typically they did not do this in a very systematic way. They were left to continue to experiment on their own for a few minutes and then they were further told several things, including: "this is a spectrogram", "it does something that relates to sound", "your task is to explore it and describe what it does". They were instructed that, in order to explore they must be systematic and explore a wide variety of sounds. This exploration period was followed with a group discussion on how voice, different vowels, whistles, claps, etc, sound and look in the spectrogram (See figure). There was a discussion of what happens when sounds are added together. The students compared various sounds and vocalizations, including Dr. Khalil throat singing, and examined their corresponding spectrograms. The students were shown how spectrograms can also be used to "sonify" images, using as an example the sonification of a portrait of Barack Obama (http://www.ultimaserial.com/UltimaSound.html). They were further shown (using sounds digitally processed by Dr. Minces) the way complex sounds can be generated by adding simple sounds filtered in narrow frequency bands. These three demonstrations generated great surprise in the students.

3.1.2 Waveforms

This section began with a brief discussion led by Dr. Minces and Dr. Khalil on the nature of sound and how to measure it (with a microphone). The students used Audacity, free software that allows them to record, visualize, and transform waveforms (the raw voltage captured by a microphone). The students then recorded themselves and looked at the waveforms. We find that most students have never watched sound and this creates an opportunity to start thinking about sound as a wave. They were guided to examine the waveforms of the recorded sounds at different time scales, thereby appreciating sound envelope (long time scale) and oscillations (short time scale). They were invited to compare the difference between the oscillation of whistling (close to a pure sine wave) and the singing of vowels (periodic but complex), and to increase or decrease the speed of the recorded sound, which in turn increases or decreases the pitch. We found that students were not familiar with this possibility and were greatly surprised by the results. There was a general discussion on the relationship between the periodicity of oscillations and the perception of pitch. Finally, the students' asked personal questions, which ranged from our musical taste, our practice as scientists, how opera singers break glass by singing a high note (resonance), or how telecommunications work.

See the following link: https://www.youtube.com/watch?v=4thOxDnYdfk&feature=youtu.be for a video excerpt of the lesson.

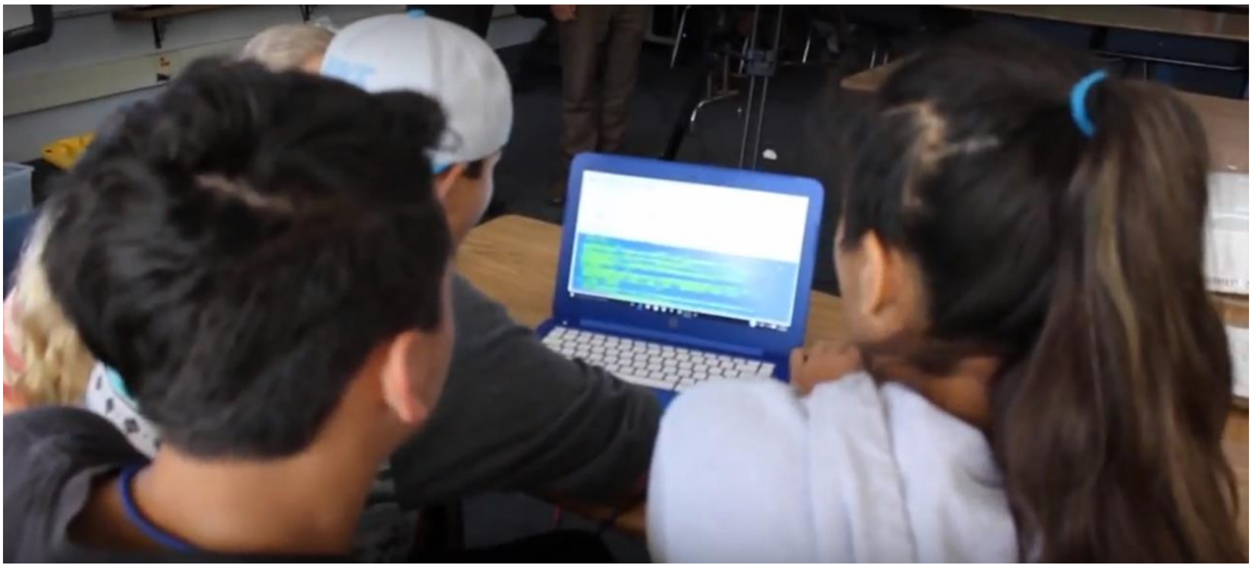

Figure 1. Students making sounds and exploring a spectrogram.

3.1.3 Sound-spotting

This activity was led by Dr. Challen. Sound-spotting involves proactively listening to sounds typically heard every day and recording those sounds. Using field microphones and contact microphones, students recorded sounds from around the school, they were able to visualize and edit waveforms using Audacity. Students worked in small groups to compose a piece of music comprised entirely of the sounds they recorded. Students explored the summative nature of sound waves, the effect of frequency on pitch and the very subjective nature of auditory perception of sound.

3.2 Good vibrations

The goal of these activities is for students to understand how objects vibrate and to relate the vibrations of the objects with the soundwaves they produce and the corresponding sensory perception. For this we use Slinkies and strings. The Slinkies work as a scaled-up model of a string, a string that can be actually seen vibrating.

3.2.1 Slinky lab

The students used Slinkies to generate standing waves. They shook the Slinkies with their hands and measured the frequency of the fundamental by counting the number of oscillations in a given period of time. They were then instructed to shake their hands faster, so they could see the Slinky vibrating in the first, second, and third harmonics. They measured the frequency of the oscillations and the location of the nodes, and repeated the experience for different Slinky extensions and different tensions (measured as coils per unit of space). In a general discussion they were helped to realize that the frequencies of the subsequent harmonics were multiples of the fundamental, and that the nodes partition the length of the Slinky in equal parts. From this lesson they grasped the actual physical meaning of nodes and harmonics, and how the type of vibration in an object relates to the frequency.

3.2.2 Monochord lab

The students built monochord instruments modeled after the Vietnamese Dan Bau, using a design provided to them by Dr. Khalil. Each instrument was built with a guitar string attached to a wooden pole. On one side the string was attached to a harp tuner (so the string could be tuned), on the other side to a flexible metal plate (so the note could be bent to make more interesting sounds), on the side of the metal plate there was an attached metal can, serving as an acoustic amplifier. The students used contact microphones to measure the vibrations (sound) of the instrument and observed the measurements in Audacity. They were instructed to find the harmonic nodes by softly touching the string with one finger and plucking the string on a different finger. Further, in a global discussion they related their observations with the Slinky to their observations with the monochord.

3.3 Other Waves

Staff Research Associate Joshua Jones from the Scripps Whale Acoustic Lab visited the school and explained to students the ways in which his profession relies on waves. Students learned about acoustic monitoring of whales and saw equipment used to detect waves in water. Students were very engaged, asked thoughtful questions and started to appreciate that sound travels through different media in different ways. The presentation also helped students appreciate the different fields in which waves are used. Some students identified this presentation as the most important thing they learned in the project.

3.4 Sound Installations

The culmination of this work was the design and creation of unique sound installations. Inspired by their interest in the way typical objects sound, plus a review of existing ideas, students created original pieces through an iterative design and review process. The process started with internet-based research on previous sound installation projects, a large part of which are linked through our website. This review provided them with a reference of possibilities and inspiration. Initial proposals were first reviewed by student peers and then by Drs. Minces and Khalil, who discussed the feasibility and technical challenges of constructing the pieces, encouraging the students to make the sounds more interesting by increasing their range and richness. The latter process typically involved sound and materials exploration, very much in the vein of scientific exploratory research. The students faced several engineering challenges in the construction of the pieces. They were aided by our team members and also by the school's seniors, who were taking an engineering class. A total of ten different designs were chosen to be created and exhibited. Students worked in small groups to engineer sound installations for public exhibition. In parallel, each group produced a documentary describing the design and engineering process and the physics concepts behind their sound installations. The documentaries are available through our website "www.listeningtowaves.com".

4 STUDENTS' EXPERIENCE

These activities show how *LTW* can integrate a subject that is highly relevant in students' lives, their own voices, other sounds they can produce, and sounds from everyday life, with scientific exploration. This is done through play and active guided exploration. Our activities integrate the study of a cross-cutting scientific concept (patterns in waves), with scientific practices such us measurement and systematic exploration, with computation and technology (recording and electronically manipulating sound). We found that very few of the 180 students that have participated in the program so far were familiar with the concept of sound as waves. Barely anyone had seen a spectrogram or the representation of a waveform of a sound. This can be exemplified by the students' testimony after taking the introductory lessons, (see table 1) for a sample of the students' reflections.

Table 1: Student reflections on initial experimentation with sounds and Audacity

"All the sounds we recorded sounded really good, but together they did not always sound good. Changing the length in the soundwave helped a lot. If you stretch out your sound and made the title waves longer and flatter, it slowed down the sound and makes it deeper. If you make the sound waves taller, it speeds it up the sound and makes it higher pitched. Shortening and lengthening the soundwaves, and adding effects on the sounds helps the make the sounds separate from the others and makes some more defined."
"The main effects that we played around with were pitch, tempo, and speed. I learned that if you change speed it stretches out the whole sound wave. If you change pitch it raises up the individual sounds in a repeating sound. Finally, if you turn the tempo up it changes a little of the pitch and speed."
"Whenever you slowed or sped up a sound clip, the wave changed. When you slowed down the sound, the wavelength was stretched out and when it was sped up, the wave length was compressed. I really liked working with Audacity, because you could easily see all these changes in action. I've never really worked with music-making software before, so it was pretty difficult for me using such a complicated program, especially since I missed the first couple days of introduction."
"Throughout his project, we used many tools such as manipulating the frequency, pitch, and volume of each wave individually. What we found was that when we changed the lower toned notes to higher volumes, they stretched further across the Audacity board, making more relaxed and mild sound waves, while low frequencies had longer wavelengths than notes at higher frequencies."

Participating in this experience seemed to open a new dimension in the way students experience the everyday phenomenon of sound, and many of them reported being surprised by the elements of the experience. According to an informal anonymous poll conducted at HTHNC, 76% of the students changed the way they experience sound, and 61% "caught themselves thinking about waves when they heard a sound". Table 2 shows examples of students' testimony regarding how participation changed the way they experience sound.

Table 2: Student reflections on the way participation changed the way they experience sound

“Whenever I play guitar, I think of waves and nodes.”
“Now when I hear a sound outside of school, I catch myself thinking about what kind of sound wave it would create and what it would look like.”
“I think just the fact of knowing really just changes it, and in my case were my piece made so little sound, I try to tune in the little sounds.”
“It has made me think a lot more about sound, it's always been there I just never thought about the physics behind sound.”

Students developed critical thinking skills when designing and engineering a new device and learned collaboration skills when working in small groups to overcome challenges and meet deadlines. Many students stated that collaborative group work was challenging but rewarding when it came together to produce a unique piece of work for exhibition. For students, the opportunity to design and build an entirely new product was the main source of their enjoyment, and exhibiting it to an audience gave them a sense of purpose. One student stated, “I enjoyed the process of learning different ways I can make sound. I really liked the experience of getting to create an instrument that made an interesting noise. Other people seemed to really enjoy it too and it made me proud.” Many students developed a better appreciation for sound, as evidenced in responses in Table 3. One student stated, “My experience has changed drastically since we’ve completed this project. I never had any idea how physics worked and getting to learn in this project was so amazing to me, I am now able to distinguish different physics concepts when it comes to sound and I am open to getting to learn much more because I don’t believe you can ever know enough”.

Table 3 - Sample student responses to what was learned during the LTW project

I think the most important thing I learned was how we can find physics through sound in things from our everyday lives, much like our final product, where we took household item and created unique sounds.
The most important thing I learned was that there are many different things that make up sound.
I learned about how waves are additive and how sound travels through different mediums differently.
The most important thing that I learned was that physics is a key factor in sound. It seems very obvious, but never really surfaced with me until this project.
Nodes, anti-nodes, and harmonics
The most important thing I've learned is how waves are interrupted

Importantly, all students reported that they learned, and 93.5 % reported that they “liked” participating. Thus, the project generated positive emotional associations with the learning experience.

5 GLOBAL REMARKS

Things that contributed to the success of the project included meetings between researchers and the educator to plan and discuss ideas; student access to researchers for critique, revision and ideas; timely responses from researchers to student inquiries; flexible school schedule to support an extended project; and the opportunity to exhibit final work at the school site. More frequent meetings between the researchers and educator could have created a more seamless execution of the LTW project, but was prohibited by the work schedules of all involved. For future implementation, meetings between researchers and educators could focus on core learning objectives for students as well as predictions about likely misconceptions amongst students. In some cases, the educator faced challenges with students around the content or interpretation that would have been best addressed by the researchers.

The most substantive challenges in this project related to resource access, most significantly, availability of technology. Students had access to a limited number of computers in the classroom, none of which were sufficiently powerful to run programs such as Audacity without frequent crashes. The ratio of students to computers during this project was approximately 3:1, leaving many students without direct access. Furthermore, not all students had access to computers at home, and homework that required computer access could not be assigned. Students that had their own laptop computers in class, downloaded Audacity successfully and were more proficient and more engaged in the work.

Limited budget and resources meant that students needed to work in small groups on the final sound installations and were somewhat restricted in the engineering and construction of their work. While this created a valuable learning opportunity, it also resulted in some students losing their connection to the project when their ideas were not chosen or were revised to accommodate resources available.

From the students' perspective, the length of the project made it challenging for them to stay engaged throughout. Projects at the school typically last 6-8 weeks and *LTW* spanned 12 weeks of school time and straddled Spring Break. Much of the extra time was needed to accommodate Audacity-related activities where computer speed and access were rate-limiting. Students would have preferred more time to design and build instruments and many identified this process as the section of the project they learned the most from, either about sound, collaborating, solving problems or engineering. A suggestion was made to commence design immediately, but continue the theoretical sound work in parallel.

6 FUTURE DIRECTIONS

Going forward, some minor adjustments will be made to further increase student engagement, including more opportunities to explore the sound waves of popular music in Audacity. Introducing popular musical instrument construction and analysis along the more theoretical part of the activities would create a more seamless connection between the artistic and scientific components of the project, increasing students' interest while providing more practical tools to develop their final installations.

LTW has the potential to generate even greater subject integration: a connection could be made with Humanities subjects to have students explore their own culture and the music associated with it. They might also explore their current musical interests and compare those with traditional music by creating simple instruments and recording sounds in Audacity. Another important connection to explore is the relation with the visual arts, since display was a great part of the final music installations. In the future, a collaboration could be made with the teachers in the visual arts class.

An important direction to take is to organize the program in a way that is compatible with more typical schools. HTHNC is a project based school, the students are used to learning by doing and the specific subject domain is not rigidly established; this allowed us to spend a long time working on the project as a natural part of the school curricula. Such freedom and availability is not possible in the majority of schools, a challenge and an opportunity for LTW is to streamline our activities to adapt them to the "typical" school curricula of science and math. We think that this is possible given the close connections between music and math, and given that our activities are oriented at exploring sound in a scientific manner that is compatible with the requirements of a science class. The work presented here is a proof of concept that art, scientific practice, computing, and engineering, can be seamlessly integrated into an educational program that, through musical sound, connects science with students' interests.

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