SONIFICATION AND SCIENCE PEDAGOGY: PRELIMINARY EXPERIENCES AND ASSESSMENTS OF EARTH SCIENCE DATA PRESENTED IN AN UNDERGRADUATE GENERAL EDUCATION COURSE

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ABSTRACT

This paper describes preliminary investigations into how sonifications of scientific graphs are perceived by undergraduate students in an introductory course in oceanography at the University of Rhode Island. The goal is to gather data that can assist in gauging students' levels of engagement with sonification as a component of science education. The results, while preliminary, show promise that sonified graphs improve understanding, especially when they are presented in combination with visual graphs.

1. INTRODUCTION

Sonification is becoming an acknowledged informatics method, and its effectiveness for communicating complex datasets has been shown in many studies [1], [2]. However, its uptake has been slow for a number of reasons. We contend that is partly due to the fact that comparatively little auditory display work has focused on issues of education and learning. This collaboration was formed to explore the usefulness of sonification as a tool for science communication and education. Undergraduates, especially non-science majors, are often challenged by having to comprehend graphs that are unfamiliar to them. We created sonifications of a number of graph types that students typically encounter in science courses. All students were invited to submit online surveys before and after they were exposed to sonified versions of graphs. Section 2 of this paper describes related work done previously in the field. Section 3 describes the nature of the graphs used in this project and the designs of the sonifications. Section 4 describes the surveys and their results. Section 5 summarizes the results and describes how this collaboration will continue.

2. RELATED WORK

While the use of non-speech sound has been shown to be informative in a number of contexts [2], in recent years we have noticed an increase of work done for purposes of outreach and communications. These projects are typically meant for student and non-specialist audiences, often in informal educational settings such as museums [3], [4]. The use of musical sound in informal STEM contexts reinforces recent findings that assert that different modalities of experiencing science are mutually reinforcing, and that integrated presentations of knowledge produce a more educated and robust workforce and research community than the traditional "specialist" model of education [5].

As for earlier examples of sonification being used in marine studies, this seems to be a fairly new domain. There is, of course, one of the most venerable use of auditory display, the sonar, which has for some time been essential to understanding underwater environments. And sonifications of ocean buoy data were presented in [6]. Beyond these two examples, we are not aware of other sonification work done in the area of oceanography.

3. DATASETS AND SONIFICATION DESIGNS

In our preliminary discussions of how to make use of sonifications in oceanography courses, we decided that a first step should be to create a variety of one-dimensional graphs through sound, thus making sonification a running theme of the team-taught general education science course OCG 111 Ocean Exploration. This course is typically populated by freshmen and sophomore non-science majors. It covers the basic tenets of oceanography and ends with a module on global change. Sonifications were created in consultation with Christopher Roman for modules that he taught.

The time series that were sonified for the course included:

- Monthly mean numbers of sunspots, spanning the period from March 1958 to November 2017 [7];
- The "Keeling Curve" [8] of monthly atmospheric carbon dioxide measurements, dating from March 1958 to September 2017;
- Tide levels at four recording stations in Louisiana, Newport, RI, San Diego, CA, and St. Petersburg,

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FL, covering the period from July 2017 to September 2017 [9];

- Global mean sea levels, spanning the period from March 15, 1958 to December 15, 2013 [10];
- Monthly land and ocean temperature indices dating from March 1958 to October 2017 [11].

All sonifications were created by Mark Ballora with the SuperCollider audio programming language [12]. The approach is parameter-based, creating “sonic scatter plots” [2] in the same manner as work described in earlier publications [13], [14], [15]. The following sections describe the nature of the sonifications.

3.1. Sunspot Sonifications

The sunspot dataset consists of monthly mean counts from March 1958 to November 2017 (Figure 1). A throbbing sound made from filtered noise changes pitch according to the contour of the curve outlined by the mean sunspot counts, and is mapped to a range of half an octave. A light shimmer is added for aesthetic purposes, meant to suggest rays of sunlight. To suggest discrete spots, a clicking sound, somewhat like a Geiger counter, clicks at a varying rate within a range of zero to 30 clicks per second, varying in proportion to the number of mean spots per month.

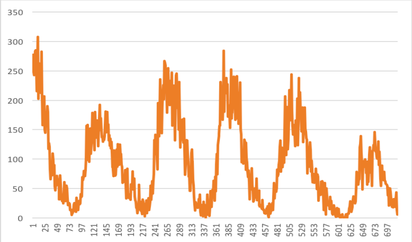

Figure 1: Monthly sunspot counts plotted per month since 1958.

3.2. Atmospheric CO_2 Levels

The Keeling Curve is often introduced in contexts of climate change. It represents monthly atmospheric carbon dioxide levels. Levels rise and fall yearly with the seasons, while the steady ascent of the overall level is evidence of increasing global CO_2 emissions. (Figure 2).

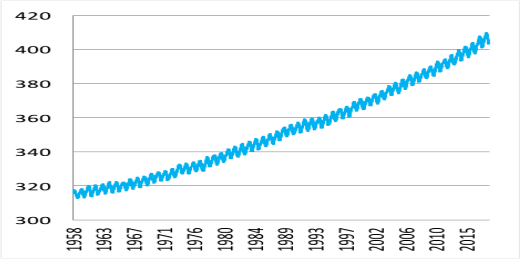

Figure 2: Keeling curve, showing monthly CO_2 levels in parts per million.

The contour of the Keeling Curve is represented by a somewhat buzzy timbre, and a pitch that spans two octaves from the lowest to the highest data point, with four months playing per second. Since this alone would be a rather bland (although accurate) sound, a complementary layer is added that is derived from the spectrum of carbon dioxide [16] (Figure 3).

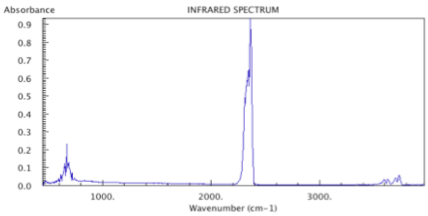

Figure 3: Spectrum of carbon dioxide (wavelengths in mm)

The wavelengths shown in Figure 3 are converted to frequencies by dividing them into the speed of light, then transposing and compressing these intervals so that they fall within the audible spectrum. The ascending curve is accompanied by a set of sine waves that are based on these relationships of the carbon dioxide partials. This secondary layer adds a bit of inharmonicity to the sound, although at a level quite a bit lower than the main “melody” instrument.

3.3. River Tide Levels

These datasets consist of tide level measurements taken every six minutes from July 2017 through September 2017. To emphasize the rhythmic but distinct tidal patterns that exist at different locations, four weeks of tidal activity were played (Figures 4a-d). The data points are mapped to pitches that fall within a span of just under two octaves, with the exception of the anomalous drop in levels in the St. Petersburg due to hurricane Irma (Figure 4d, bottom), which can be heard as a drop of an octave. The pitches are played by a sine-like tone that is meant to sound watery.

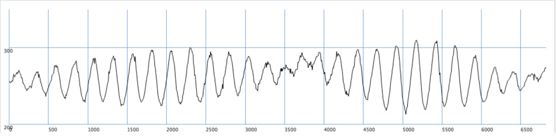

Figure 4a: Tide levels, Louisiana July 1-29, 2017

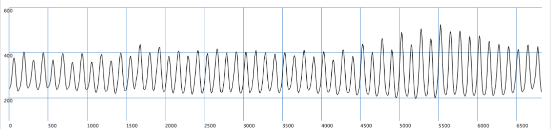

Figure 4b: Tide levels, Newport, RI, July 1-29, 2017

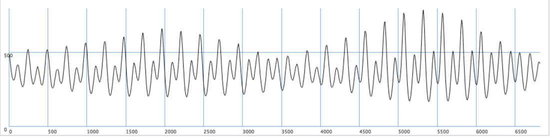

Figure 4c: Tide levels, San Diego CA, July 1-29, 2017

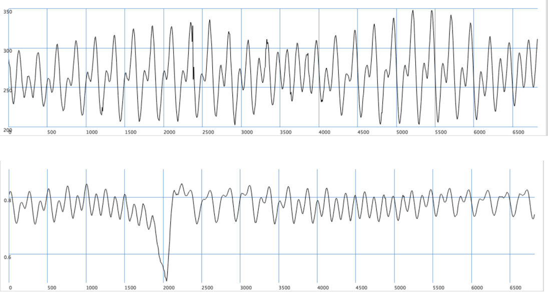

Figure 4d: Tide levels, St. Petersburg, FL
July 1-29, 2017 (top), September 2-30, 2017 (bottom)

3.4. Sea Levels

The sea level time series shown in Figure 5 is mapped to pitches that ascend three octaves, played by a windy/watery timbre. In addition to the main graph, which covers the period from 1880 to 2013, a shortened version starts at March 1958, which can be played simultaneously with the sunspot and Keeling Curve datasets.

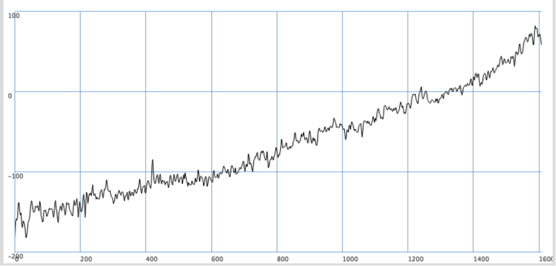

Figure 5: Global mean sea levels, measured monthly, January 15, 1880 to December 15, 2013.

3.5. Earth Surface Temperatures

The global temperatures plotted in Figure 6 are mapped to a timbre consisting of a filtered combination of a sawtooth wave and Brown noise (sometimes called $1/f^2$ noise). The pitch and brightness reflect the sea levels, which span an octave over the course of the data. A second version of this sonification was created that renders the rightmost portion of the graph, from March 1958 to October 2017, so that it may be played simultaneously with the sonifications of the sunspots, Keeling Curve, and sea levels. The overall sound is meant to convey the short-term (yearly) variability in global temperature along with the steadier longer-term (decadal) increase occurring over the longer time period.

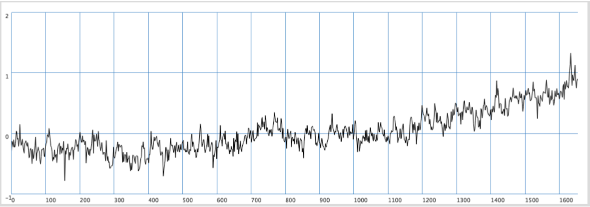

Figure 6: Monthly Land and Ocean temperature indices dating from 1880

4. METHODS

Students enrolled in an introductory oceanography course were invited to complete online questionnaires. No personal information was collected. The protocol was approved by the Institutional Review Boards (IRB) of both the Pennsylvania State University and the University of Rhode Island.

The tide levels were played for the students as an informal introduction to the idea of sonified graphs, during a course module that covered tides and currents. Four weeks of activity, corresponding to July 2017, were played, which covered two rising and falling tidal cycles. For St. Petersburg, a file was also rendered that consisted of the activity in September 2017, since this included the drop in water levels that resulted from hurricane Irma. Each tidal sonification was rendered to last 30 seconds. Students were presented with the sounds and then shown the graphs in Figure 4. They seemed generally able to match the sounds to the correct graphs, and to have a good appreciation for the rates of tide change.

More formal evaluations, designed by Robert Pockalny, took place during the global change module that ends the course. This class session consisted of presentations of the Keeling graph, sunspots, surface temperatures, and sea levels. The playback time for the files that spanned 1958-2017 was 20 seconds. This duration allowed a number of files to be played back during a class period without jeopardizing students' attention spans. Files of the sea levels and surface temperatures dating from 1880 were rendered at a proportional timescale, which meant that they lasted 46 seconds. Two combinations were also played: 1) the Keeling curve/surface temperatures/sea levels and 2) surface temperatures plus the "clicking layer" of the sunspot sonification. Chris Roman created a combined display in MATLAB® software [17] that consisted of a moving dot progressing along the graphs as the sonifications played.

The audio files may be downloaded at https://bit.ly/2wczYmB.

4.1. Initial Survey

Before the sonifications were presented in class, students were asked to complete an online survey that was meant to characterize their perceived knowledge for various science and climate-related topics. Surveys were submitted by 53 out of 106 students. The results are shown in Tables 1-4.

Table 1: General Science Knowledge

Far below average	Below average	Average	Above average	Far above average
2%	13%	51%	26%	8%

Slightly above average (3.25 rating. 3 as expected average)
Standard deviation: 0.84

Table 2: Climate and Climate Change Knowledge

Far below average	Below average	Average	Above average	Far above average
4%	21%	47%	28%	–

Average (3 rating, 3 as expected average)
Standard deviation: 0.8

Table 3: Familiarity with Natural Cycles Related to Climate

Not at all familiar	Not so familiar	Somewhat familiar	Very familiar	Extremely familiar
14%	38%	40%	4%	4%

Below average (2.46 rating, 3 as expected average)
Standard deviation: 0.64

Table 4: Ability to Interpret Graphs

Far below average	Below average	Average	Above average	Far above average
2%	6%	64%	26%	2%

Slightly above average (3.2 rating, 3 as expected average)
Standard deviation: 0.92

4.2. Post-Sonification Survey

A second questionnaire was made available after students had been exposed to visual and auditory graphs. This was designed to get a sense of their understanding of material presented through sound. The second questionnaire was submitted by 23 students. The results are shown in Tables 5 through 11.

Table 5: Which answers describe the relationship between the sunspots and global temperature? (Select all that apply)

	Pre-Sonification (50 respondents)	Post-Sonification (23 respondents)
Sunspots occur on an 11-year cycle, and are likely causes of periodic changes in global temperature.	20%	30%
Sunspots occur on an 11-year cycle, but are not likely causes of periodic changes in global temperature.	22%	39%
An increase in sunspots frequency correlates with an increase in global temperature.	36%	43%
An increase in sunspots frequency does not correlate with an increase in global temperature.	14%	13%
What are sunspots?	8%	–
Don't know	32%	9%

Table 7: Which best describes the change in global temperature since 1880?

	Pre-Sonification (50 respondents)	Post-Sonification (23 respondents)
No significant change	2%	–
Initially not much change, but a more rapid increase recently.	66%	87%
Initially a rapid increase, but not much change recently.	10%	4%
Initially not much change, but a more rapid decrease recently.	6%	4%
Initially, a rapid increase, but not much change recently.	4%	–
Don't know.	12%	4%

Table 9: Effectiveness of "Climate Sounds" and graphics to understand patterns and trends of climate change

A great deal	15%
A lot.	23%
A moderate amount	50%
A little	4%–
None at all	8%

Table 10: Effectiveness of "Climate Sounds" and graphics to understand causes and effects of climate change

A great deal	19%
A lot.	23%
A moderate amount	38%
A little	15%
None at all	4%

Table 6: Which answers describe the relationship between the CO_2 record at Mauna Loa (i.e. Keeling Curve) and global temperature? (Select all that apply)

	Pre-Sonification (50 respondents)	Post-Sonification (23 respondents)
The overall increase in the CO_2 trend follows the global temperature record.	44%	57%
There is no relationship between the CO_2 trend and global temperature record.	6%	4%
The annual variability in CO_2 is due to seasonal differences in wind patterns.	6%	22%
The annual variability in CO_2 is due to seasonal differences photosynthesis.	24%	17%
The annual variability in CO_2 is due to seasonal differences in temperature.	6%	43%
There is no annual variability in CO_2.	–	–
What's the Keeling Curve?	12%	–
Don't know.	34%	17%

Table 8: How variable has the global temperature been since 1880?

	Pre-Sonification (50 respondents)	Post-Sonification (23 respondents)
Uniform	–	–
Overall, a general increase in temperature with 10- to 20-year variations/undulations in the overall trend.	73%	65%
Overall, a general decrease in temperature with 10- to 20-hear variations/undulations in overall trend.	13%	13%
Uniform increase in temperature	7%	13%
Uniform decrease in temperature	7%	4%
Don't know.	–	4%

Table 11: Which approach did you find most effective for advancing your knowledge about patterns, trends and cause/effect relationships associated with climate change?

Graphs alone are most effective	23%
Sounds alone are most effective	8%
The combination of graphs and sounds are most effective	54%
All about the same	15%

5. DISCUSSION

5.1. Survey Results

The number of submissions of the second survey was lower than we would have preferred. There is no definitive way to identify why this was the case. The surveys were optional with no incentives offered for participation. While this simplified the IRB process, it left open the possibility of a low response rate. Without higher yields, results can only be considered preliminary. But the responses that were submitted indicate overall that: students found the addition of sounds to be effective, and the sound renderings were an aid in understanding the science content.

The results of the question about the relationship between the sunspots and global temperatures (Table 5) indicate potential misunderstandings for some respondents, shown in the first choice. There is an increased number of students that indicate that sunspots are likely causes of global temperature changes—20% indicating this as correct before hearing the sonifications, and 30% indicating this as correct after hearing the sonifications. In fact, the second and third answers are correct: an increase in the number of sunspots correlates with increases in global temperatures, but they do not cause them. There are approximately equal numbers of increased incorrect and correct answers on the second, post-sonification questionnaire.

The second question asked about the relationship between the Keeling Curve and global temperatures (Table 6). Here again, results were mixed. After the sonifications were played, there was an increase in the percentage of correct responses for the first choice, from 44% to 57%, which identified an increase in the CO_2 trend as following the global temperature record. There was also an decrease in the selection of the fourth (incorrect) choice, that annual CO_2 variability is due to seasonal photosynthesis, which dropped from 24% to 17%. After the sonifications there were increases in two incorrect answers: the third selection, that annual CO_2 variability is due to seasonal differences in wind patterns, rose from 6% to 22%; the fifth selection, that annual CO_2 variability is due to seasonal temperature differences, rose from 6% to 43%. Overall, there seemed to be an increase in knowledge of the Keeling curve and its relationship to temperature after the sonifications were played, although there were still 4 of 23 respondents (17%) on the post-sonification survey who indicated that they did not know whether there was a relationship between them.

The greatest improvement in correct selections in the post-sonification test had to do with identifying how global temperatures had changed since 1880 (Table 7), which rose from 66% to 87%. Those who completed the second survey were able to hear the rapid increase in temperatures, which reinforces an oft-quoted justification for the use of auditory displays: the strength of the ear in discerning patterns.

There was a slight shift from correct to incorrect answers on the question about variability in global temperatures since 1880 (Table 8). This suggests the possibility that some students misunderstood the term "variable."

Tables 9 and 10 indicate that the majority of students found that the sonifications improved their understanding. Perhaps the most telling responses had to do with preferences of displays for understanding patterns, trends, and cause/effect relationships (Table 11). The great majority found that the combination of visual graphs and auditory displays were the most effective, rather than one or the other.

5.2. Future Work

Now that a suitable audio design and format has been created, there is nothing to prevent these files from being used in future offerings of this course.

Preliminary work has also been carried out in sonifying populations of copepods in Oxygen Minimum Zones of the oceans. This is an area of active research in the field of oceanography, of which Karen Wishner is a leading figure [18], [19]. Oxygen Minimum Zones (OMZs) are mesopelagic ocean features with extremely low oxygen. They are predicted to expand geographically and in intensity with global climate change, which potentially impacts ecosystems, fisheries, and economies. Copepods are small, often microscopic-sized crustaceans. A variety of species are represented in terms of the average number per cubic meter of water, at increments of 100 meters, from the surface to a depth of 1000 meters. A topic of active investigation is the diel vertical migration (DVM) in which larger zooplankton and fish descend to about 300m depth during the day to avoid predators and ascend to the surface at night to feed. The extent of this migration compared to their body size is remarkable and not yet fully understood.

The next stage of work done under the auspices of this grant funding will be to sonify diel vertical migrations of various copepod populations within these zones. The educational intention will be to enhance learning of complex ocean processes in the undergraduate classroom. We anticipate that these auditory renderings can also help reveal correlations and unexpected interactions between zooplankton distributions and the environment that will be useful to researchers in the field.

5.3. Concluding Thoughts

The results, while preliminary, show promise. We regard this collaboration as aligning well with a long-term goal: to engender a generation of students who consider science as something that is understood through hearing as well as seeing. We expect that, for many students, musical sound can provide a more holistic and intuitive understanding of scientific phenomena than is possible through visual presentations alone.

We should stress, however, that by saying this we do not mean to imply that sonification is superior to or a substitute for time-honored methods of visual display. But there is good reason to feel that the addition of auditory displays to other graphing methods will add value to scientific engagement and understanding. In the keynote to ICAD 2017 [20], Carla Scaletti quoted Bruno Latour, who asserted that sciences produce objective knowledge through multiple arguments. Knowledge is never advanced by an isolated mapping. Rather there are always multiple mappings – instruments, theories, calculations, charts, graphs, etc. – that form a "cascade of inscriptions" that in a chain of reasoning that leads to a conclusion. New knowledge is the result of multiple interdependent inscriptions, which combine to legitimate new conclusions.

Our hope is that projects such as this one can be steps in a healthy "cascade of inscriptions," steps that have a positive impact on science pedagogy by making scientific exploration appealing to wider audiences and by predisposing the next generation of researchers to seek discoveries through hearing as well as seeing.

6. ACKNOWLEDGEMENT

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