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Scientific Data Sonification

Data sonification, simply put, is the practice of representing data with sound. In parallel with data visualization, the sonification process aims to facilitate the interpretation of large collections of scientific data by providing alternative ways of experiencing them.[1] It can also serve for artistic, accessibility, and popular science purposes. In this paper, we investigate how data sonification can contribute to scientific insight, how it relates to the artistic aspects of producing music, and how it impacts distinct audiences. In particular, we look at two different projects that were well-received by both academic and general populations: the sonification of data from the Hubble Space Telescope (HST), and the use of sonification to teach protein folding reactions at the University of Illinois Urbana-Champaign.[2] We argue that part of the reason why these were so successful can be attributed to the intense collaboration between scientists and musicians throughout the production process. The analogous situation in the data visualization world — scientists and graphics designers coming together — is a lot rarer, and we postulate some reasons why. We also address how combining sonic and graphical representations allows for a richer understanding of structures contained in the data.

Before delving deeper into the subject, it is important to understand that we will only discuss "scientific sonification." While there are various ways of synthesizing sound from data, only a few will yield a faithful representation of the original dataset.[3] Scientific sonification is the requirement that one should — in principle — be able to reverse the process with no loss of information. Of course, this does not exclude the possibility of representing aggregate statistics: if an audio clip is generated based on time averages of some quantity, we do not expect information about specific values to be contained in the clip, but we do expect that the calculated averages were incorporated in some way in the audio.

In general, any data-to-sound conversion technique will fall under one of three categories: audification, parameter-mapping, or model-based sonification.[4] The first one is the simplest method one can think of: each unique datapoint is mapped to a corresponding audio waveform. For example, seismologists can "listen" to earthquakes by converting strong (or soft) vibrations of the earth into high (or low) pitches, allowing for seismic waves to be directly interpreted as sound waves.[5]

1. H.G. Kaper, E. Wiebel, and S. Tipei, "Data sonification and sound visualization," *Computing in Science & Engineering* 1, no. 4 (1999): 48–58, https://doi.org/10.1109/5992.774840.

2. Kimberly Arcand, Matt Russo, and Andrew Santaguida, "A universe of sound," Chandra X-ray Center, System Sounds, 2020, accessed March 15, 2024, https://chandra.si.edu/sound/; Carla Scaletti et al., "Sonification-Enhanced Lattice Model Animations for Teaching the Protein Folding Reaction," *Journal of Chemical Education* 99, no. 3 (2022): 1220–1230, https://doi.org/10.1021/acs.jchemed.1c00857.

3. Kaper, Wiebel, and Tipei, "Data sonification and sound visualization."

4. Ellwood Colahan, 2023, accessed March 15, 2024, https://mlaetsc.hcommons.org/2023/01/18/data-sonification-for-beginners/.

5. Florian Dombois, "Using audification in planetary seismology" (Georgia Institute of Technology, 2001).

The second method works just like synthesizers and digital audio workstations: specific parameters of the data are converted into different characteristics of the sound.[6] In climatology, for example, you could think of representing temperature and humidity variations by changes in pitch and volume. In contrast, applying audification to the problem would mean trying to convey the temperature and humidity at every point in space, which is not very useful for humans.

The third method involves converting observed patterns and trends of the data into musical structures such as chords, rhythms, and melodies.[7] This is the most complicated type of sonification, as it requires a high level of expertise in music and in the field of study from which the data comes from. Because it gives space for creativity in how the mapping between sound and data is done, it tends to be a lot more successful than the other two approaches.[8] Thus, it should come as no surprise that model-based sonification is a highly collaborative endeavor, and the two successful examples studied in this paper made use of it.

With these methodologies in mind, we now move on and investigate how exactly NASA converted astronomical data from the HST into beautiful melodies that — according to the public — "sound like" the original images captured by the telescope. The project, which is an initiative of the Chandra X-ray Center (CXC), was led by astrophysicist Dr. Matt Russo, musician Andrew Santaguida, and visualization scientist Dr. Kimberly Arcand.[9] Multiple astronomical images have been sonified by the group, and each of them utilizes a completely different model. For example, an audio clip of the Milky Way center was generated by "scanning" the corresponding image left to right, with the direction and intensity of light being converted into pitch and volume. Stars and other bright astronomical objects are represented by individual notes, which compose an enjoyable melody. Clouds of gas and dust are modelled by an evolving drone.[10] Moreover, when different types of light are observed (e.g. visible and x-ray), they correspond to different instruments. Dr. Russo explains that these models play with rhythm and expectation, and that's why they work so well.[11] This claim might sound strange at first, as one might argue that since not many people have had contact with scientific sonification before, they can't have expectations on it. However, listeners likely have had prior contact with astronomy, even if only at the basic level. The emotions associated with that experience are the generators of expectation in this case. As Christopher Witulski puts it, "things like globalization, memory, nostalgia, and culture play out in listening."[12] Thus, familiarity plays an important role in how we shape our opinions about music, and this familiarity can come in various forms. The feelings of wonder and curiosity, typically associated with images of galaxies and the universe, are leveraged by the

6. "Learning Synths," Ableton, accessed March 15, 2024, https://learningsynths.ableton.com/.

7. Thomas Hermann, Andy Hunt, and John G Neuhoff, eds., *The Sonification Handbook* [in en] (Berlin, Germany: Logos Verlag Berlin, December 2011).

8. Hermann, Hunt, and Neuhoff.

9. Arcand, Russo, and Santaguida, "A universe of sound."

10. Arcand, Russo, and Santaguida.

11. Matt Russo, "What does the universe sound like? A musical tour," TEDxUofT, 2018, accessed March 15, 2024, https://www.ted.com/talks/matt_russo_what_does_the_universe_sound_like_a_musical_tour/transcript.

12. Christopher Witulski, "Rhythm and Expectation," *World Music Textbook: Vol. 2* 2, no. 1 (2021): Article 3, https://doi.org/10.25035/wmt.2021.003, https://scholarworks.bgsu.edu/wmt/vol2/iss1/3.

CXC sonification team to create music that evokes the same feelings in the listeners. This exceptional matching between the visual and auditory senses is what makes the results "sound right," and the reason why they appeal to general audiences.

According to Dr. Russo, the appeal to these senses is also a key component to the popular science side of this project.[13] Once the public is engaged with the subject, it is easier to bring more science into the conversation through more music analogies. For example, the supermassive blackhole at the center of our galaxy sounds like a crescendo in the sonified Milky Way center.[14] Other sonification procedures also make it possible to explain the resonant motion of exoplanets orbiting distant stars in terms of musical harmony.[15]

Moreover, the power and effectiveness of this method in public engagement work is even more evidenced for blind and low vision audiences. A research study by Dr. Arcand has shown that this public has stronger emotional responses, higher levels of enjoyment, and increased interest in the topic after exposure to sonified data.[16] The same study has shown that sighted users acquire a better understanding of how others access data, and the experience contributes to an increase in the perceived value of accessibility initiatives.[17] Beyond their artistic and cultural value, the sound representations of astronomical images also directly impact how researchers think about their data and accessibility in the professional world. For example, Wanda Díaz-Merced, a blind astronomer, discovered that sonification of data increased the sensitivity to signals correlated with black holes in the source images.[18] Since sound is multi-dimensional, it provides a unique way of analyzing noisy datasets and uncovering patterns that would be otherwise hidden in a graphical representation.[19] Thus, sonification techniques not only improve accessibility to individuals with vision impairment, but also add another powerful instrument to the toolkits of all astronomers.

The fact that the work done by CXC has had influences outside the popular science sphere and has reached the professional astronomy world shows that scientific sonication has the potential to impact other fields. The focus on academic benefits like these is what drives the second example investigated in this paper. Researchers at the University of Illinois at Urbana-Champaign have recently found that sonification techniques can be used as an efficient pedagogical tool to teach concepts that depend on understanding complicated patterns.[20] Their specific use-case was in teaching undergraduate and graduate students the various protein folding reactions. Describing protein folding is like giving directions to someone lost in a maze: at each step there are multiple decisions to be made, each one impacting the next. A good chemistry student will have a sense for which decisions are good or bad (i.e. they can accurately identify the low-energy protein configurations). Similarly, some sequences of notes

13. Russo, "What does the universe sound like? A musical tour."
14. Arcand, Russo, and Santaguida, "A universe of sound."
15. Russo, "What does the universe sound like? A musical tour."
16. Kimberly Arcand et al., "An accessibility case study incorporating rich visual descriptions for Chandra's high-energy universe," *SPECIAL EDITION*, 2023, 25.
17. Arcand et al.
18. Wanda L. Diaz-Merced et al., "Sonification of Astronomical Data," *Proceedings of the International Astronomical Union* 7, no. S285 (2011): 133–136, https://doi.org/10.1017/S1743921312000440.
19. Diaz-Merced et al.
20. Scaletti et al., "Sonification-Enhanced Lattice Model Animations."

are typically preferred over others because they sound more enjoyable or intuitive to most people.[21] Based on this principle, the teaching program created by Scaletti et al consists of using demo animations coupled with sonification techniques to improve students' performance. The scientists incorporated the sonified videos in a set of lecture materials and homework assignments that introduce the four key concepts of protein folding. The structure of these videos consists of playing a different note for each distinct protein configuration shown on the screen. Thus, a videoclip showing the transitions between different configurations can be coupled to a sequence of notes. These notes were carefully chosen by the researchers using Kyma, a sound design language that allows them to incorporate the specific constraints and structure of protein folding into the selection of notes.[22]

The scientists tested the effectiveness of this teaching method by formulating chemistry questions both in the "traditional" way and in the form of sonification problems. Students were presented with both types of questions after being exposed to the lectures and sonified videos. Scaletti et al found that under these circumstances students performed better, on average, in sonification problems, even though the contents were the same across both tasks.[23] In addition to that, the sonified animations increased students' interest in the subject and were perceived as useful in solving other homework problems related to folding dynamics.

In this context, the success of the project can, once again, be largely attributed to how scientists and musicians collaborated in the sonification process. This was done both indirectly — via the musicians working on the development of Kyma — and directly — via feedback from music students who were also exposed to the same set of materials. As with the previous example, the efficacy of sonification relies on avoiding conflict between our preconceived intuitions and sensations induced by sonified data. For example, because most people associate "high" and "low" with frequency, it is a smart idea to directly translate high energies and low energies into different pitches (as opposed to timbre, which would likely make the audience confused). Various elements of music cognition are involved in this principle. Even though no one has ever listened to a protein folding before, people will have expectations on what it would be like because music evokes emotions, and emotions are universal. According to Kyung Myu Lee, "listeners develop mental schemas for music from their experience" and "through repeated exposure to music, listeners build expectancies to musical events."[24] Thus, a good sonification protocol must acknowledge that our senses are not independent: what something looks like, what it sounds like, and what it feels like must all be in some form of logical agreement. If that is not the case, the practice could hinder the learning process by introducing excess information.[25]

Based on the two examples discussed in this paper, we can conclude that sonification is most effective when coupled to other techniques such as visualization. This is because our

21. Josh H McDermott, "Auditory preferences and aesthetics: Music, voices, and everyday sounds," in *Neuroscience of preference and choice* (Elsevier, 2012), 227–256.

22. Carla Scaletti, "Computer music languages, Kyma, and the future," *Computer Music Journal* 26, no. 4 (2002): 69–82.

23. Scaletti et al., "Sonification-Enhanced Lattice Model Animations."

24. Kyung Myun Lee, "Music cognition: investigations through the centuries" (June 2017), 475.

25. Scaletti et al., "Sonification-Enhanced Lattice Model Animations."

primary sense is vision, but it can be drastically enhanced by auditory stimuli.[26] Sonification helps us understand what is difficult to visualize, such as multidimensional data and patterns, while visualization helps us understand what is difficult to hear, such as tiny details in a large image. Moreover, we note that a common feature of sonification projects is that they can increase accessibility, allowing blind and low vision individuals to experience and interpret datasets that are typically restricted to visual representations. The methodology and principles developed for sonification could easily be generalized to other accessibility initiatives and multisensory experiences. Notably, the finding that sonification techniques depend heavily on understanding listener intuition and establishing diverse teams that specialize in both the musical and technical aspects of the activity is an important one, and it should not be overlooked. The two projects discussed in this paper exemplify a wide range of applications for scientific sonification, including public engagement, teaching, accessibility, and research. Because they are so diverse, working on each one will require a different set of skills, further corroborating the hypothesis that good sonification is only possible through collaboration.

26. McDermott, "Auditory preferences and aesthetics: Music, voices, and everyday sounds."

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