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The Utility of Sonification

Sonification is the process of translating data sets into sound or music for artistic, scientific, or practical purposes. As a tool, sonification can facilitate the interpretation and comprehension of information by perceiving it in a traditionally unusual manner - aurally, through expressions and variations in volume, pitch, timbre, and more. However, each of these factors present their own limitations and strengths, due to their nature as well as due to human perception, which must be considered when creating an audio display. Through sonification, the line between artist and scientist is often blurred, as this field attracts a wide interdisciplinary following since its future potential for useful application is still being explored. This paper will examine the various ways in which sonification is currently being used in multiple disciplines, as well the dynamics of sound as they relate to human perception.

An auditory display is generally described as any display that uses sound to communicate information. It encompasses all aspects of the human-machine interactions and environment,

including speakers, machines used, and the gathering and computing of the information. One part of this is sonification, which is the process used to create an audio display . As a fairly new field, sonification has been growing more defined. In 1999, Kramer et al. (1999) specified sonification as "the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" (p.4). About a decade later, an alternative definition proposed more confined parameters: "the data-dependent generation of sound, if the transformation is systemic, objective, and reproducible" (Herman, 2011). Taking these definitions together, we derive that sonification intends to interpret the relationships between data using sound in a way that acknowledges the human perceptual thresholds in order to communicate the information comprehensively and effectively.

There are some simple applications of sonification which we experience daily, as they are integrated into our everyday lives. We can see this in the ring of a cell phone when a call is received, the wail of an alarm clock in the morning, or the countdown of a security alarm. These are all great examples of one category of sonification: alarms, alerts, and warnings. In each of these instances, a piece of data was received, such as a phone call from a friend, and then that data was intentionally

translated into a sound, such as a ringtone. The importance of "intentional sound" is what separates sonification from incidental sound. For example, when a baseball bat whams a baseball, the loudness and pitch of their contact may provide information on how far the ball is going and even to some extent the direction it will travel, but this is not by design or intention and is therefore incidental sound. Despite how common "intentional sound" based interactions have become, sonification still has the potential to grow as a field. However, one inhibiting factor to it's proliferation may be the lack of common knowledge regarding the properties of sound.

The three auditory dimensions which are most commonly manipulated in sonification are pitch, loudness, and timbre. Understanding the human thresholds of interpreting these factors is important to consider when creating an audio display. For example, the average human is capable of discerning a pitch from frequency waves ranging from about 20 Hz to 20,000 Hz. That's about 10 octaves of pitches in standard Western notation, and with each octave containing 12 notes, that adds up to about 120 discrete pitches. While this is a fairly large medium to work with, human hearing is actually capable of discerning many more differences in pitch than are utilized in Western notation. The measurement of detectable differences in pitch is called

frequency difference limen (FDL). The FDL is less than 1 Hz at a frequency of 100Hz. For reference, the difference between a G and a G sharp at this interval is about 5.8 Hz. At 1 kHz, the FDL is 2-3 Hz (Hermann, Hunt and Neuhoff, 2011). For reference, the difference between a half-step in pitch at this octave is about 60 Hz. This shows the potential for a huge amount of information to be conveyed even in this small 60Hz spectrum, as within this one musical half-step are at least 20 unique discernible frequency changes. Utilizing this information provides thousands of corresponding frequencies for data points to manipulate.

The average person currently has an existing relationship with pitch, whether consciously or otherwise. Therefore, in some circumstances, it may prove useful to adhere to Western standard pitches rather than the full spectrum of frequencies. For example, if an audio display is created using a discrete set of pitches that pertain to one scale, these notes could then be communicating extra information. The tonic of a scale, for example, is commonly described as feeling like "home," while the 4th note in the scale, if played with the tonic, could provide a feeling of suspense reaching for a resolution. While this could pose a problem, alternatively, these intrinsic musical relationships can also be used to the advantage of the audio

display. If not done intentionally, however, the relationships between these pitches may inadvertently convey information that is not relative to the data set.

There is also an interrelationship between pitch and volume. In frequencies less than 2k Hz, pitch tends to decrease with intensity, while the higher frequencies above 4k Hz behave oppositely (Hermann, Hunt and Neuhoff, 2011). There are many other phenomenon to take into account when using pitch as well. For example, a series of harmonically related frequencies can give the perception of a lower fundamental frequency even when it is not present. If frequencies of 880, 1320, and 1760 Hz are emitted, they are all sequential harmonic overtones of the 440 Hz frequency. The human listener will perceive this as fundamental note of 440 Hz being sounded and the other frequencies as harmonic overtones of that fundamental. In this same example, if that fundamental frequency of 440 Hz is then included with the other three frequencies, the perceived pitch remains the same (440 Hz), but the timbre becomes noticeably different, which introduces yet another complex interrelationship (Hermann, Hunt and Neuhoff, 2011).

Timbre is the culmination of harmonic characteristics that give instruments their uniquely identifiable sound. When a violin and a viola play an "A" note at 440 Hz, they are emitting

the same fundamental frequency. However, by the timbre, or tonal qualities, they can be differentiated as two different sound sources. This is due to the varying amplitudes of harmonic frequencies present when that note is played, which grant its unique timbre, as well as the envelope (ASDR) of the sound. This combo provides a lot of potential for sonification. Each voice, instrument, animal, and more has its own timbre. Furthermore, there are timbres which have not yet been created or discovered. The culmination of these timbres contributes a wide set of tools for creating audio displays, as well as some potential obstacles. Using the same example of the viola and violin, many people may not readily identify these as two different instruments depending on their tonal integrity, implementation, as well as the ear of listener. The timbral qualities shared between many instruments and the illusive acoustic nuances which separate them present a unique set of challenges when approaching sonification.

However, there have been some interesting studies regarding comparisons between sounds. The use of neuroimaging has shown that when processing incoming audio, the regions of the brain that are responsible for motor activity are activated. For example, in one study, when subjects were asked to listen to a rhythmic pattern in anticipation of repeating it later, their

motor areas were active. Furthermore, these same motor regions were active even when the participants were not instructed that they will need to repeat the pattern later (Chen, J. L., Penhune, V. B., & Zatorre, R. J. 2008). In similar studies, pianists have shown motor region activation when simply listening to piano music (Bangert et al., 2006.) However, when presented with the same music, non-pianists do not show any motor region activation. A similar study was done where subjects were presented with "action sounds" that were relatable to human interaction such as using a zipper and crushing a can, and "non-action sounds" which had no relation to human motor behavior such as waves on the beach or a passing train. It was found that the motor areas of the brain that are activated by these "action sounds" are the same areas that are activated when these subjects actually perform these actions. However, when presented with the "non-action" sounds, the subjects show no activity in the motor areas (Kohler et al., 2002). This additional connection to "action sounds" has the potential to be utilized in sonification through further study, as it shows that sounds already associated with familiar actions may have a more meaningful impact on the interpreter than arbitrary noises.

Amplitude is measured in decibels (dB), and a change of 1 dB is noticeable to most ears, but not by much. Since decibels

are a logarithmic measurement, this shows that decibels use exponentially more power in order to double the perceived volume. any increase of 3 dB is technically doubling the acoustic power, while 10 dB increases the sound energy 10 fold, and 20 dB 100 fold, etc. However, psycho-acousticians inform us that humans perceive a doubling of loudness about every 10 dB (Sengpiel, 2017). Beginning the scale from the low end of 0 dB, it begins to top out at 118 SPL as fifty percent of humans begin to experience discomfort. This is also known as the threshold of feeling, while 140 dB is referred to as the threshold of pain. However, despite these thresholds, it's worth noting that permanent hearing loss can occur with extended listening sessions over 85 dB (Huber, 2013).

Taking these factors into account, this places some limits on the utility of amplitude in sonification, as the scale of 0-85 db is far smaller than pitch. Furthermore, although theoretically amplitudes of 0-85 dB could safely be used in sonification, external factors may present limitations on this range's effectiveness. If the audio display is not being listened to in a quiet environment, than any of the data in the lower dB range will be lost. For context, a whisper can be measured at about 30 dB. Similarly, if the audio display is being used in a public place, innocent bystanders may be

bothered by the sonic data long before the 85 dB threshold. Additionally, loudness memory recall is especially poor when compared to memory recall for pitch (Hermann, Hunt and Neuhoff, 2011). For these reasons, while amplitude can be a useful tool in sonification, it is not the most flexible or dynamic.

Another necessary tool of sonification, as it is inherent to the medium, is time and rhythm. Since sound is experienced through a canvas of time, this element is inseparable from an audio display. Fortunately, it is also one of the strongest. There are several tasks that our visual system can perform better, such as spatial localization. But, when it comes to rhythmic and temporal perception, the auditory system tends to shine. One lifesaving sonification device which has proven this true is the heart rate monitor. In emergency rooms, doctors and nurses must work quickly under pressure, and their hands and eyes can be fully occupied with pressing tasks. By translating the heartbeat of a critical patient into a clear, loud beeping sound that is emitted throughout the room, the entire medical staff is able to interpret this information simultaneously in real time and react accordingly. Not only does this free up their eyes and hands in a time of crisis, but it frees up a pathway for urgent communication by eliminating the need for constant verbal pulse updates. Since every human has an innate

connection to the rhythm of their own heart, this pulse method of sonification is easily and quickly understood, as well as effective.

In each of these instances, we are only seeing one piece of data that is being interpreted and then triggering an audio response, functioning as an alert. The applications of sonification can be broadly categorized into four general sections:

1. alarms, alerts, and warnings
2. status, process, and monitoring messages
3. data exploration
4. art, entertainment, sports, and exercise

The more complex applications of sonification interpret several pieces of data and then communicate the relationships between them, which is much less commonly experienced. These approaches are used in a wide variety of fields, with proven utility in seismology, bio-medicine, and space. Its existence is itself interdisciplinary, as sonification borrows from the fields of sound engineering, physics, acoustics, cognitive science, psychology, musicology, computer science, and more.

It may seem reasonable to question the purpose of sonification when visual displays seem to be satisfactory in accomplishing the goal of communicating data effectively. While at times this is true, there are some simple, practical reasons which support the use of sound to convey information. In the case of electronics, computers are shrinking, and with them the screen size, to the point today where we have cell phones and smart watches which are essentially very small computers. As the level of visual space available to convey information decreases, this can be compensated by transitioning some of that data into sound. One study completed in 2002 looked to explore the usefulness of sound in shrinking displays by comparing the ability of a user to complete tasks on digital calculators with varying button sizes (pixels 16x16, 8x8, and 4x4) and sonic feedback. It was found that sound significantly improved usability for both small and standard button sizes - more data could be entered with sonically-enhanced buttons and subjective workload reduced. Furthermore, more sophisticated sounds, which presented more information, were more effective than the standard device sounds (Brewster, 2002). This study shows not only the usefulness of sound in conveying data, but particularly its use in maintaining maximum productivity in the advent of shrinking visual mediums. Furthermore, it highlights the

importance of the complexity of the sound used in communicating the most information with the maximum efficiency.

In some situations, one's visual capacity may already be overloaded or otherwise occupied. In emergencies, information can be urgently conveyed when sight is obstructed or otherwise in use. The second category can often be utilized here - status, process, and monitoring messages. Some examples of this include blood pressure monitoring, patient data in an anesthesiologists workstation, brain surgery. One user study was completed by Plazak, J., Drouin, S., Collins, L. and Kersten-Oertel, M. (2017) to determine the utility of sonifying the distance between the probe and the anatomical target within an existing neuronavigation platform to be used during brain surgery. This study explored five possible sonification solutions, which help illustrate the various approaches that can be taken to complete the same objective. They include:

1. Sine tone frequency matching: Frequency limits were set at 130 Hz and 440 Hz, with one sine wave constantly present at 440 Hz. As the distance decreased (probe reached its destination in 3D space), the frequency of a second variable sine wave ascended until it matched with 440 Hz, indicating the successful placement.

2. Sine tone pitch mapping: Nearly identical to the previous method, except the lower limit was set at 263 Hz, and the changes in distance resulted in discrete pitch changes consistent with a chromatic musical scale.
3. Pulsed tone sonification: This sonification used a short sine tone (400 Hz) that pulsed, increasing in frequency as distance decreased until finally reaching a continuous tone.
4. Signal-to-noise sonification (SNR): White noise was heard exclusively when the distance was greater than 600mm, while a pure sine tone (400 Hz) was heard exclusively once the target was reached. The relationship between these two sounds was linear, so at 300mm, they were heard 50/50.
5. Binaural beat sonification: Two square waves were used, one steady at 220 Hz. The second variable wave could be altered within 5% of that pitch, which created a "binaural beating" effect, which was resolved once the distance was closed.

It was discovered that all the sonification techniques resulted in an improved accuracy of the surgery when combined with the visual aspect, but the SNR technique did have a significant advantage over the other techniques. While this study did not venture to explore why, it suggests that SNR techniques may have useful applications in the future (Plazak et al., 2017).

The third class of "data exploration" is that which the term "sonification" is most often referring. This functions to offer a more comprehensive representation of the data, and convey information about an entire data set, or aspects of that data. As early as the 1960s, seismologists were discovering the utility of sonification by recording local earth tremors as frequency modulations on magnetic tape. The most efficient way to examine and interpret this stockpile of readings would be play back the tape at high speed so that the researchers could listen for any interesting events ("Sonification Now Hear This", 2017). This creative approach was ground-breaking, as it opened the door to a new way of analysis.

The fourth category of art, entertainment, sports, and exercise has a wide variety of applications. Some simpler games have appeared in audio-only versions, such as tic-tac-toe and *Space Invaders*. Another example is a game titled *Papa Sangre*, which was developed intentionally with no video in order to be accessible by the blind and vision-impaired, though it can be enjoyed by anyone. In this game, you control the movements of a character trying to avoid obstacles, traps, and other patrolling enemies. The gamer, wearing headphones, hears his/her footsteps while exploring the level and must navigate around obstacles and enemies relying solely on the sounds of the generated

environment. This game is essentially a self-contained interactive sonification game. It has since been removed from the Apple Store, but the VR game engine has become open source, allowing other developers to capitalize on their great binaural audio foundation for new projects (Bennun, 2015).

Another example of interactive sonification is a system recently created to convey the intricate movements of fish inside an aquarium (Pendse, Pate and Walker, 2008). Like *Papa Sangre*, this was developed with the intention of providing a more engaging and accessible experience for people with vision impairment. This project involves several steps. First, the movement of the fish is tracked, gathering various information, such as speed, location, and movement. This data is then transferred into various musical elements, including instruments, pitch, tempo, etc. The dynamic movement of life in an aquarium can be difficult to explain with words, and this provides a great example of the inherent utility and capabilities of sonification. While this requires a great deal of science and technology to accomplish, the goal is also artistic as it attempts to capture the feeling of watching a live aquarium - not just the actual movements of the fish - and translate that into a meaningful audio display.

Sonification has proven useful by unlocking patterns in data in order to make meaningful discoveries. Through the four expanding categories of alerts, monitoring messages, data exploration, and art, people are realizing new impactful applications that are having a positive effect every day. The real-time applications are valuable in improving performance in key fields, transforming experiences for the visually impaired, and increasing the precision of delicate surgeries.

Sonification has existed before it was ever defined, and now that its potential is being explored, the possibilities are endless.

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