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Integrating Sonification Into a Lesson on Joint and Combined Variation:

Literature Review

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Introduction

This Literature Review will discuss certain aspects from the field of sonification, education, and learning. The domain of sonification addresses the topic of representing data with sound. Audio representations are a good way of presenting multi-variate data intuitively, and may be especially effective for auditory learners, who learn best through the sounds they hear. Joint and combined variation is the mathematical subject concerned with the relationships between three or more variables that each vary directly or inversely with each other. Though sonification is an established field of study, the applications to education have not been thoroughly explored.

Sonification

Simply put, sonification is the process of representing data using sound. The field of sonification is quite broad, but most uses of sonification involve interpreting data [1]. Sonification is often used to provide audio feedback in cases when alternatives or enhancements to visual feedback are desired or can be more helpful [1]. For example, if one wishes to observe the strength of the vibrations of a certain material, it may be awkward to portray vibrations with visuals but natural to represent them with sound. In the following section, various techniques from existing literature are presented to provide the reader with a background to the field, followed by an overview of the interpretability and relevance of sonification, and a brief analysis of the sonification programs Cheddar, Sonifeye, and Sonification Sandbox.

Techniques

There are three main techniques for sonification: audification, parameter mapping, and physical modeling synthesis [1]. Audification involves directly mapping a data stream into pressure versus time graphs, which results in pressure waves that humans interpret as sound.

Audification is the simplest sonification technique, and sonifications generated from audification are often hard to understand without experience. Parameter mapping is more complex and involves the translating of certain data to parameters that regulate characteristics of sound, also called auditory dimensions, such as pitch (fundamental frequency), volume, duration of notes, and time. Parameter mapping can be effective and comprehensible without much prior experience. Because there are many auditory dimensions which can be numerically adjusted, parameter mapping is good for sonifying multivariate data as an alternative to presenting 3 or more data series on one graph. Physical modeling synthesis, also called model-based sonification, attempts to control properties of sound that are associated with physical properties, often directly moderating timbre. Timbre is the aspect of sound that differentiates different vowel sounds or different instruments, and is related to the shape of a sound wave. For example, a model-based sonification might include audio that sounds like water dripping into a cup with varying amounts of liquid inside to represent the volume of a sample over time. Model-based sonifications are generally the most intuitive and comprehensible. However, the physical properties associated with a sound, such as how full a cup sounds, may not change regularly as the individual properties of sound like volume are altered, so complex data techniques are required for physical modeling synthesis. [1]

Stereo surround sound systems can mimic the effect of sound coming from different directions. Spatial sonification uses perceived direction and volume to map physical position in data to the perceived location of sound in space [2]. The context or richness provided by spatial sonification can help listeners intuitively parse more complex, multidimensional data. [2]. Stereo can also be used to differentiate between two data sets by playing one data set to one ear and another data set to the other [4].

For certain purposes, real-time interaction with data is desired, which can make interactive real-time sonification useful. Real-time sonification also allows increased familiarity with sonification, as changes to data can be associated automatically with changes in audio feedback [2]. However, regular sonification techniques often take too long for real-time sonification due to the amount of data processing required, so interactive sonification systems must be optimized for rapid performance [2].

Minimizing alarm fatigue is also a focus of many more recent sonification programs. One of the main reasons sonification is used for certain augmented reality systems is to improve user concentration by alleviating clutter from visuals [3]. However, if sonifications are irritating or too obtrusive, listening to them for long periods of time can cause alarm fatigue and thus be counterproductive in increasing long-term productivity. One of the common problems that can make sonifications excessively irritating or obtrusive is high volume, or more often sharp or pointed sounds resulting from irritating timbre. [3]

Relevance

Sonification is used in the domain of science for interpreting data and in the arts for composition. In art, work focuses on aestheticism, and audio is often post-processed to sound pleasing [2]. In scientific fields, sonification is used as a tool to interpret data, so accuracy is highly valued. Though aestheticism is not as often prioritized, it can help reduce strain, which allows for prolonged meaningful use of sonification as a way to interpret data [2].

Sonification is frequently used in augmented reality systems as a way of providing audio feedback [3]. Visuals can become cluttered, which often reduces the effectiveness of presenting information visually, as there is a limit to how much data the eye can focus on at once [3]. Offloading some of the visual feedback to an audio format can alleviate strain and allow for the user of an augmented reality system to quickly interpret profuse data by processing a combination of audio and visual feedback [3]. In addition, certain data are easier to interpret as sound. For example, the force with which an object is struck can be mapped to volume, and this might be more intuitive and easier to interpret than the length of a vector arrow.

Interpretability

Sonification has been used by Alonso-Arevalo et al. to provide audio feedback on curve shape and curvature [5]. This research was done in the context of the SATIN project: developing an augmented reality system that allows one to explore and interact with objects in 3-dimensional space similarly to how one explores objects on a 2-dimensional screen with CAD software. Providing feedback on curvature and curve shape is important because they influence how light reflects off the surface of an object, and thus impact aesthetics. The study found that sonification allowed users to analyze curve shape and curvature, as participants successfully identified points of maximum and minimum curvature and points of inflection using sonified audio feedback. The study also employed a kinetic module which post-processed sound to make it more natural and intuitive, but the study did not find significant improvement through use of the kinetic module, implying that physical modeling synthesis will not always reliably improve user experience. The study also suggested that fundamental frequency most effectively provided information to users when analyzing sonifications. [5]

Complex sonification involving multiple properties of sound is often difficult to understand when first heard, and there is a learning curve when using sonification [1]. However, Bonebright et al. found that sonified graphs which mapped two dimensional data to time and fundamental frequency could be matched to their visual counterparts with fair accuracy by students with no background in sonification [4]. In addition, multivariate graphs which mapped two data sets to the pitches of two different instruments were also paired by students to visual graphs with fair accuracy, though with less accuracy than bivariate graphs [4].

Sonification Programs

There are many programs currently available for sonifying data, including Sonification Sandbox, Sonifeye, and Cheddar. Sonifeye is a sonification program that produces audio feedback in the form of sonification for the use of multisensory augmented reality which allegedly requires minimal training to comprehend and apply [3]. The researchers who developed Sonifeye avoided constant feedback and only played sounds based on significant changes so that users would stay alert to feedback instead of growing accustomed to it, thus reducing alarm fatigue. For high precision tasks like holding a needle at a certain angle, users care more about the slight variations from the desired angle, and do not need to be constantly informed if they are holding the needle at the correct angle. The study tested their program with an experiment where participants attempted to touch the surface of a liquid under an electronic microscope with a needle and identify times of contact while keeping the needle at a specific angle. This is comparable to the task of injecting DNA into bacteria, because one would regularly locate a needle or syringe and a cell under a microscope using visual feedback from a computer-generated image when direct observation is impossible. The study found that using sonification to provide audio feedback on angle and location led to better precision than using a standard visual system. The study also found similarly positive results from using both sonification and the visual system, suggesting that a combination of audio and visual feedback may be ideal. [3]

Another sonification program, Cheddar, focuses on interactive spatial sonification [2]. Cheddar sonifies data with parameter mapping, and uses stereo to create the effect of sound moving in space. This allows users to shift their point of view when interpreting data, so they can look at data from different perspectives and thus notice features of data that are difficult or impossible to perceive otherwise. Cheddar bases its sonification on the density and spread of data. For example, it treats sizeable and spread out data from geological rock mechanics differently from data that is more compressed. The app sonifies up to six variables. Cheddar was intended to be used for both art and science, thus it supports more aesthetic mappings or more accurate mappings, according to the needs of artists and scientists. [2]

Sonification Sandbox is a Java-based program that is simpler and intended for non-professional use [8]. Most other sonification programs are made for niche audiences and often depend on software which is not commonly accessible, as many sonification programs are intended for AR systems with proprietary software. Since Sonification Sandbox is a Java-based application, it can be run on virtually any platform that supports Java. Sonification Sandbox is also accessible to a non-professional audience due to its intuitive interface, which allows users to map data in a spreadsheet to timbre, pitch, volume, and pan. In addition, the ability to import .csv files, a common file type for spreadsheets, allows users to edit the data set they wish to sonify in a program such as Excel, Google Sheets, or almost any spreadsheet editing software. Sonification Sandbox also allows users to edit data in a spreadsheet within the application and modify how the data is mapped to different sonification parameters. Once data and settings have been set, the program generates a graph of the data and a corresponding sonification, which can be exported separately as media files or together in an .htm file. [8]

G. Dubus and R. Bresin reviewed sonification strategies for 495 research projects sonifying physical properties and chose 60 projects to study in depth. They analyzed trends among sonification research, including the most common variables that were mapped to different characteristics of sound and the frequency of the use of various auditory dimensions. The table below summarizes their results. They found that fundamental frequency, or pitch, was the most common auditory dimension used in parameter mapping. [9]

Table 1. Most used mappings of sixty analyzed projects

Number of Occurences	Mapping
24	Location → Spatialization
18	Location → Pitch
12	Distance → Loudness
10	Density → Pitch
9	Distance → Pitch
8	Density → Duration
7	Orientation → Pitch
7	Size → Pitch
6	Velocity → Pitch
6	Motion → Pitch
6	Motion → Spatialization
6	Energy → Loudness
6	Signal amplitude → Loudness
6	Signal spectral energy distribution → Pitch

This tables summarizes the most frequently used mappings among the sixty projects analyzed by G. Dubus and R. Bresin [9].

Table 2. Most used mappings of sixty analyzed projects

Auditory dimension Percentage of the total number of mappings	Percentage of the total number of mappings	Number of auditory dimensions used significantly less often
Pitch	23.8	29 (100%)
Loudness	15.2	27
Duration	10.1	25
Spatialization	9.5	25
Tempo	5.9	21
Brightness	5.1	18
Timbre	3.6	14
Intrumentation	3.6	14
Spectral Power	2.8	9
Spectral Duration	2.4	5
Pitch Range	2.0	3
Center Frequency of Filter	2.0	3

This table summarizes the usage frequency of auditory dimensions among the sixty projects analyzed by G. Dubus and R. Bresin [9].

Learning Styles

There are multiple different learning style models, but one of the most important ones is the Visual-Auditory-Kinesthetic learning styles model, which is based on student response and interpretation of external stimuli [7]. Though the three categories of learning styles are kinesthetic, visual, and auditory, most learners are some combination of the three [6].

Visual

Visual learners absorb information best through visual means. Facial expression along with body language and other visual cues are observed attentively by visual learners and influence the intake of knowledge. In addition, visual learners absorb information best from visual content of lessons such as diagrams and pictures. [6]

Kinesthetic

Kinesthetic learners are hands-on learners that learn through exploration and experimentation. They prefer to engage with material by touching and moving to examine the world around them. Kinesthetic learners also enjoy activity-based courses with experiments or activities involving physical movement, as investigative activities engage them and help them absorb information best. [6]

Auditory

Auditory learners use nuances of sound to help them absorb information. They often find listening to a teacher and other students or discussing material to be beneficial to their learning experience. In addition, auditory learners use pitch, speed, and tone of voice to help them gain understanding of lectures, similar to how visual learners use facial expression and body language. Courses geared towards auditory learners should include oral delivery or presentation rather than text alone. Although pure auditory learners are rare, many people are partial auditory learners, which means that many students can benefit from including auditory teaching elements in lessons. [6]

Joint and Combined Variation

Joint and combined variation is the topic in mathematics which is used to describe the complex relationships between three or more variables that vary directly and/or inversely with each other. Examples of combined variation include the ideal gas law and the equation for gravity, as they relate more than two variables and each pair of variables is either directly or inversely proportional. In addition, many chapters in textbooks on joint and combined variation address relationships in which one variable is proportional to another variable raised to some rational power, as this follows naturally from the concepts of joint and combined variation. Since joint and combined variation involve relationships between more than two variables, sonification may be an effective method for presenting examples of joint and combined variation, and may be especially useful for auditory learners.

Conclusion

Many techniques have been established for sonification, but the applications of sonification have yet to be thoroughly explored, especially the educational applications. Currently, sonification is mostly used by professionals, but tools like Sonification Sandbox allow educators who may not have much experience with sonification to sonify data in ways that can improve their lessons. Joint and Combined Variation is a topic where applying sonification is natural because the subject describes relationships between many variables which are difficult to exemplify visually. In addition, the impact of integrating sonification into education has not been widely examined, nor has the influence of sonification in lessons on auditory or partial auditory learners who may benefit the most from sonifications due to their learning style.

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