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Perception of multi-varied sound patterns of sonified representations of complex systems by people who are blind

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Abstract

Listening to complexity is a long-term research project, which addresses a central need among people who are blind: providing equal access to the science classroom, by allowing them to explore computer models, independently collect data, adapt and control their learning process. The innovative and low-cost learning system that is used in this project is based on the principle of perceptual compensation via technologies, by harnessing the auditory mode to transmit dynamic and spatial complex information, due to its unique affordances with respect to vision. Sonification of variables and events in an agent-based NetLogo computer model is used to convey information regarding both individual gas particles and system-wide phenomena, using alerts, object and status indicators, data representation and spatial audio displays. The paper describes two experiments: (i) auditory perception of varying types of auditory representations, spatial trajectories of a modeled object's motion, relative intensity, and frequency; and (ii) auditory perception of complex sound patterns, exploring detection and recognition of multiple sound channels at different complexity levels of sound patterns. The research would serve to improve our understanding of the auditory processes by which perception of sound patterns takes place and transforms into a conceptual model. The long-term practical benefits of this research are likely to have an impact on science, technology, engineering and mathematics (STEM) education for students who are blind.

Keywords: Blindness, learning, STEM, computer models, sonification

Introduction

The project addresses a central need among students who are blind: that of accessing information in exploratory learning of science. Students who are blind have been integrated into public schools for more than 60 years and are required to complete the same curriculum and assessments as sighted students. However, they are prevented from access to firsthand

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information, as many science education resources are based on the visual channel (1). In the past 40 years several manuals have been written on how to teach science to students who are blind and visually impaired (2-4). However, research into their application and impact on learning is sparse. Few learning environments based on assistive technologies have been created to support science learning, such as the use of a force-feedback mouse to learn physics (5, 6).

Auditory information technologies for people who are blind

The learning process of people who are blind is based on gathering information through perceptual and conceptual tools (7). At the perceptual level, the shortage in visual information is compensated for by other senses such as the haptic, auditory and olfactory senses. Similar to other supportive environments, the Listening to Complexity (L2C) system is based on the principle of perceptual compensation via technologies (8). L2C harnesses the auditory mode to transmit dynamic complex information. The choice of an auditory display results from three considerations: (a) the auditory mode transmits information that changes both in space and time, similar to the visual mode and different from the haptic mode; (b) the auditory mode easily interfaces with large bandwidths at fine frequency-discrimination and intensity-discrimination thresholds (9); and (c) the auditory system is used to dealing with complex and rapidly changing sound patterns (10). In fact, it has been found that individuals who are blind can recognize 2D shapes through audition that activates the right dorsal extrastriate visual cortex (11). Sonification is the presentation of information using non-speech sound (12).

Over the years, it was found that congenitally blind subjects were able to recognize auditory coded visual patterns related to hand movement (13). Subjects not only memorized simple associations between sounds and patterns, but also learned the relationship between the auditory code and spatial attributes of the patterns. Research into the impact of different components of sound on auditory perception has shown that increasing the number of channels beyond three causes degradation in comprehension (14) and that a greater frequency separation between sound streams results in better stream segregation (15).

In the current project, we go beyond these studies in several ways. On one hand, we use sound to represent a dynamic rather than a static array. Moreover, the referents of the dynamic representation are multiple and operate at two system levels. Finally, we test how systematic variation of several different sound pattern features impacts detection and recognition of multiple channels, extending research into auditory perception. Some systems were developed to support Science, Technology, Engineering and Mathematics (STEM) education among students who are blind, such as the Talking Tactile Tablets (16) based on audio and 2D tactile materials, supporting interaction with 2D images for learning mathematical and science diagrams. The Line Graphs technology is based on auditory and haptic feedback and is geared to learning mathematics (17). The reported studies continue to research into auditory compensation for visual information among students who are blind and extend it to both perception of dynamic and complex displays and learning about dynamic complex systems. The two experiments tackle a major challenge and require a leap above the current state-of-the-art in several research disciplines such as Computer Science, Learning Sciences, Auditory Perception, and Human-Machine Interaction. We seek a deeper understanding of the neuroscientist Bach-y-Rita’s phrase on brain plasticity: ‘We see with the brain, not the eyes’ (18). To reach this overall goal we focus on two main experiments:

- Auditory perception of varying types of auditory representations, the spatial trajectory of a modeled object’s motion, relative intensity and frequency of sound.
- Auditory perception of complex sound patterns, varying the number of sound streams, identity of the sonification components, their number, relative intensity and frequency.

Methods

The study included ten participants selected through snowball sampling for both experiments. A severe limitation is the small number of blind students in the proposed age bracket in Israel, resulting in a relatively small sample. They were chosen based on six criteria: at least 15 years old; comfort in use of computers; not multi-handicapped; normal hearing; total blindness; and onset of blindness at least two years prior to the experimental period. The participants' age range was 15-36, an average of 24 years old, five participants were female, eight were congenitally blind, five participants had residual vision but none used this in their everyday life. All the participants are proficient computer users, all learned STEM in their preliminary and high schools. All participants were with normal hearing, four participants played a musical instrument and one was member in a choir. The researchers obtained a sample of ten students, with similar proportions in terms of gender, age, and musical knowledge. The consenting guardians were made fully aware of the research framework and the specific experiments.

Variables

Nine independent variables were defined. The first three variables are connected to the research participants: age of onset of blindness; gender; and musical background. The next three variables are related to Experiment One: sonification type (musical instruments, inanimate objects' sounds, man-made sounds, and animal's sounds); spatial trajectory of the modeled object's motion; and sound frequency. The last three variables are associated with Experiment Two: sound intensity (loudness); complexity of sound pattern (event frequency and complexity); and number and type of sound streams. Three dependent variables are defined: preferences among sonified representations (rating of the pleasantness of the sound – Most disliked (1); Dislike (2); Neutral (3); Like (4); and Most liked (5)); response time; and error rate in sound pattern recognition.

Research instruments

This research included four implementation tools, and four data collection tools. The four implementation tools were the following:

Research apparatus. The recorded sounds were played through an Excel file running under Windows 7 on a personal computer equipped with stereo headphones (Sennheiser, HD580). All the sounds were played at 50% of the PC volume capability.

Set of sound patterns Experiment One. A set of 31 sound patterns, developed with experts of dynamic sound patterns, include: object-object collision (7 patterns), object-wall collision (7 patterns), speed was represented in three different ways – dashed speed represented speed by creating sound at regular distance intervals resulting in more frequent sound when the object was faster (4 patterns), sound pitch-as-speed, with pitch height representing speed (4 patterns), pitch space speed represented is based on the stereo sound (right left) and intensity (loud-close, soft-far) according to the speed and the particle's location in the space (4 patterns); each of these representations with varied frequency (5 patterns). All the sounds were based on earcon (associative auditory feedback used to represent an event), or created by the computer's MIDI musical instruments, or recordings of inanimate objects' interactions and man-made sounds, or animal sounds. For example: object-object collisions were represented by a hand clap; air bubbles passing through water; glass tapping on glass; metal tapping on metal; billiard ball hit by the cue. We examined these sounds at five different frequencies: 500; 1000; 2000; 4000; and 5000. This set of sounds meets requirements regarding frequency range (500-5,000 Hz) and loudness (75dB) with respect to sensitivity of the human auditory system, duration (200 millisecond), wave structure, 16 bit per sample, and stereo stream.

Sound tests for Experiment One. All the 31 sound patterns were tested twice by using different recorded scenarios in two different tests: comparison tests (e.g., which sound is preferred to represent speed? Sound A vs. Sound B) and scale – preferences among sonified representations (Most disliked (1); Dislike (2); Neutral (3); Like (4); and Most liked (5).

Sound tests for Experiment Two. Based on results from Experiment One, five sound representations were chosen for Experiment Two. 36 combinations of these five sounds were created, meeting the requirements regarding frequency range (4,000 Hz) and with respect to loudness sensitivity of the human auditory system (75dB), duration (30 second), wave structure, and stereo stream.

In addition to the above, four tools were developed for the collection of quantitative and qualitative data: (i) Background questionnaire (15 items): personal information, science education, computer technology use, musical background, and information about hearing ability; (ii) Research protocol: two research protocols were developed, one for each experiment. These were structured as described in the procedure section below. The Research protocols for Experiment One and Experiment Two; (iii) Observations: participants' behaviors were video-recorded (Experiment Two only); and (iv) Excel file structuring and accessing the design of the sounds in the research protocol.

Data analysis

To evaluate the participants' performance in the two experiments, the results were coded directly by the researcher into an Excel file. These results were analyzed using quantitative software (Excel) to determine the relative preferences regarding sounds for each referent.

Procedure

All participants were examined individually in their home. In the first session the participants completed consent forms and a background questionnaire. Next, they were tested with Experiment One. After six months they were tested with Experiment Two. Each experiment included five parts: a short verbal explanation about the experimental process; researcher demonstration; practice and training by the participant; experiment part 1 (20 minutes); intermission (30 minutes); and experiment part 2 (20 minutes). Each of these protocols was conducted twice, 1 to 2 weeks apart.

Discussion

In the described experiments ten participants took part in two experiments: Experiment One, auditory perception in which auditory representations were varied along various dimensions and Experiment Two, auditory perception of complex sound patterns, recognition of the sonified referents. The results of these experiments have important implications for continued research, and impact learning of people who are blind learning via sonified learning materials.

Some of the Experiment One results highlight the importance of sonifying with sounds that are semantically related to the referent. For example, billiard ball collisions were preferred for sonifying object-object collisions (two billiard balls, of the same material, collide with each other) with respect to glass tapping on glass. The Navajo drum-beat was preferred for representing the object-wall collisions (an object (one material) collides with a wall (leather drum-head)). The participants didn't select animal or digital sounds and preferred recorded real life objects with related meanings. Also, as a speed representation, most of the participants selected the dashed sound, for which frequency of the dashes corresponds to the speed, and not the pitch-space sound that requires additional cognitive processing for aligning the representation (pitch) with the referent (speed). The 2×2 methodology, using the two sessions (data collection sessions) with two tests (comparison and scale tests) aided the researchers in reliably determining the selected sounds.

Finally, we test how systematic variation of several different sound pattern features (type, number of audio streams, correctness of sound pattern recognition, and auditory perception tools) impacts detection and recognition of multiple channels, extending research into auditory perception, furthering support of the learning process of people who are blind based on auditory feedback. The research results show that the participants were able to handle up to three events and audio graph sounds at the same time. It proved difficult, however, to identify four and five sounds (events and audio graphs) concurrently, so it is preferable to avoid this level of complexity in a sonified learning process. Experiment Two examined different components of sound that might affect identification ability. Research into the impact of different components of sound on auditory perception has shown that a greater frequency separation between sound streams results in better stream segregation (15). Surprisingly, we found that when hearing heterogeneous sound, the participants identified fewer sounds compared to when hearing homogenous sounds. However, with gradual exposure to new sounds 60% of the participants were able to identify four and five sounds.

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