Studying Listener Comprehension of Sonifications through Visual Replication

Neel S. Patel, Darin E. Hughes
SREAL Lab, Institute for Simulation and Training, University of Central Florida
Orlando, FL
npatel@ist.ucf.edu, darin@cs.ucf.edu

ABSTRACT

To address the limitations of human-computer interfaces (HCIs) that rely purely on visual means of information communication, it is necessary to expand information communication to non-visual modalities. This project examines the viability of using sonification, or non-speech audio, and the parameters of pitch, intensity, and tempo, as part of non-visual HCIs by assessing the accuracy of listener comprehension of sonifications.

Specifically, this study explores both the accuracy with which a listener can visually replicate an auditory pattern and the cognitive context of this audio-to-visual translation. It was hypothesized that an untrained listener presented with a sonification would be able to create a corresponding visual representation with a high degree of accuracy ($\mu>50\%$), and that certain characteristics of the visual graph (i.e. the presentation of axes) would affect the nature and accuracy of this replication. A group of 50 subjects spanning demographic categories was given a set of 12 sonifications and asked to create corresponding visual representations. The control group was given only blank space to create the graph on, while the experimental group was given blank space, axes, and grid points, each for 4 trials.

The results indicate a 76% accuracy rate in users visually replicating an auditory pattern, showing evidence that users can extract and comprehend meaning from the patterns in a sonification. The analysis shows slight differences in accuracy levels between the experimental and control groups with significant differences by key demographic factors.

In conclusion, the hypothesis was supported by the data, showing the viability of sonification for information communication. By examining comprehension through the industry-relevant method of visual replication rather than previous experiments in pattern matching, this study demonstrates the potential of applying sonification to overcome visual fatigue in time-critical battlefield scenarios, provide HCIs for the visually impaired, and facilitate data analysis through multimodal information communication, among other fields.

ABOUT THE AUTHORS

Neel S. Patel is a researcher in the Synthetic Reality Laboratory (SREAL) at the University of Central Florida's Institute for Simulation and Training. Neel's primary focus of research over the last 4 years has been in understanding the human perception of auditory information. His most recent work in the area of applied sonification explores ways in which presenting non-voice information through sound can be used as an effective alternative to presenting that same information through visual displays with a specific focus on understanding factors around human perception and interpretation of the information being presented.

Darin E. Hughes is research faculty at the University of Central Florida's Institute for Simulation and Training. He is the lead audio research and sound designer for the Media Convergence Laboratory. His research interests include auditory perception, spatial audio, sonification, and biofeedback. He has work on simulations funded by the US ARMY, NAVY, and Airforce, the National Science Foundation, and many others.

Studying Listener Comprehension of Sonifications through Visual Replication

Neel S. Patel, Darin E. Hughes
SREAL Lab, Institute for Simulation and Training, University of Central Florida
Orlando, FL
npatel@ist.ucf.edu, darin@cs.ucf.edu

INTRODUCTION

Our use of technology is limited by the design of the technology itself. As situations that require users to process, comprehend, and respond to large quantities of information in a timely manner are becoming more common, we are reaching the limit of the amount of information that we can communicate through visual displays alone without fatiguing or overloading users. In order to address this problem, it is necessary to fundamentally transform and expand human-computer interfaces (HCIs) to include information communicated through non-visual modalities and perceived through non-visual senses. By leveraging the relatively untapped nature of non-speech sound for information communication, it may be possible to transform HCIs beyond purely visual modalities, potentially revolutionizing HCIs just as the graphic user interface did 30 years ago.

Sonification is the use of non-speech audio and the dimensions of pitch, intensity, and tempo to convey information or identify patterns in data. ***This paper presents sonification as a viable alternative to visualization by demonstrating high accuracy rates of listener comprehension of sonifications.***

The use of an auditory-based HCI will extend data representation to an entirely new realm, bringing data exploration to new audiences and revolutionizing HCIs for all users. The underutilization of the auditory cortex as well as the immersive nature of sound, allowing 360° mobility and multitasking prohibited by traditional visual displays, serve as grounds for the use of sonification in human-computer interfaces. However, before we can begin widespread applications of sonification for information communication, it is first necessary to understand both how to optimally ***create*** sonifications and how listeners will ***perceive*** these sonifications. This study assesses the cognitive perception of sonifications by expanding graph comprehension research to the auditory realm in order to understand the *fundamental process* of listeners extracting information from sonifications and the *accuracy* of this process. By understanding how listeners mentally perceive sonifications, it will be possible to design sonifications to elicit optimal listener comprehension.

STATE OF THE FIELD

Sonification is a fairly young field of science; as a consequence of focused study having begun only 20 years ago, the field has yet to delineate methods for creating optimal sonifications based on situational and user-audience factors. A crucial goal of the field is to create a general format for design of sonifications, allowing the field to advance beyond scenario-specific or ad-hoc applications.

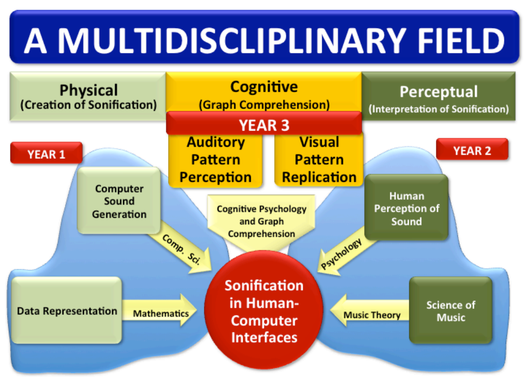

Figure 1. Description of related fields

Auditory Displays and Precursors to Sonification

In his 2002 paper, Herman defines the distinction between sonifications and auditory displays as follows: auditory displays are any transmission that leads to audible perceptions for a user, including speech interfaces and alarms or auditory notifications, while sonification maps specific changes in a dataset to changes in auditory parameters (most commonly those of pitch, intensity, and tempo). In short, auditory displays communicate *that* something is happening, while sonifications communicate *exactly what* is happening.

The advantages of acoustic displays include allowing increased mobility and multitasking capabilities by leaving the visual modality free for other primary tasks, which has allowed practical application of auditory displays in situations that would be otherwise limited by traditional visual displays. Basic examples include alarm notifications, which communicate the occurrence of a specific event to a listener. More advanced uses include the pulse-oximeter, which maps information such as heart rate to pitch or loudness, and the Geiger counter, which communicates radiation levels through auditory means. Both examples effectively communicate to the user the occurrence of changes in a dataset without necessitating the use of a visual display. Such auditory displays demonstrate the potential applicability of sonification and sound for more complex and advanced uses (Herman, 2002).

Pollack and Ficks were among the first researchers to explore the viability of communicating information through sound in order to gain a comprehension not possible through the use of a visual display. It is important to note that while the processes used in their experiment were a step toward developing a foundation of sonification, it was not considered to be a true sonification. In their 1954 experiment, Pollack and Ficks indicated that multiple dimensions of sound used in conjunction with one another were more effective than a uni-dimensional display (Kramer, 1994). Speeth later established the viability of auditory in his 1961 experiment on the classification of audio data of the seismic readings of two groups (bomb blasts and earthquakes) by human listeners. His experiment showed that with minimal training, humans were able to interpret audio representations of data and classify them into the correct group. Bly's 1982 experiments showed that comprehension of auditory displays was as accurate as comprehension of visual displays. Furthermore, comprehension of the two combined was significantly more accurate than comprehension of either alone. These research papers formed the basis upon which the core theory of sonification has been built starting in 1987.

An outline of current trends in sonification reveals that areas lacking in development include establishing practical and real-world uses of sonification; most instances of sonification continue to be too specialized or narrow for widespread application (Kramer et al., 1997 and 2010). Before the practical application of sonification can be realized, it is necessary to create a ***theory for sonification design*** that takes into account situation-specific (the conditions under which sonification is being applied) and demographic (target audience for the sonification) characteristics of the intended use.

Phase One and Two of Research

Previous phases of research have focused on understanding basic creation of sonifications as well as the comprehension rates and reaction times of listeners presented with these sonifications. Phase one involved developing a novel sonification creation program, allowing a user to import a dataset and create a sonification, including user-customizable characteristics of sampling rate and range of audio values. Phase two of the study assessed a basic measure of comprehension through pattern matching and reaction times to sonifications. Results indicated a high (60%) accuracy rate in matching a sonification to one of four visual graphs as well as an accurate reaction to an auditory pattern within one second in 82% of trials (Patel, 2010). These studies began by assessing basic levels of sonification perception in terms of demographic factors of listeners as well as auditory parameters of the sonification itself, providing a platform for further inquiry into optimal sonification design.

ADVANTAGES OF SONIFICATION

Several properties of sound give audio information communication, or sonification, advantages over traditional visual communication. Sonification can "provide background information about changed states without a major disruption of attentional focus" (Watson and Sanderson, 2004). Sonification can be used to present high-dimensional data without creating information overload for users as well as allow simultaneous background (peripheral, rather than direct observational) tracking of changing temporally complex variables (Kramer et al., 1997).

A main advantage of sonification is that sound is immersive, and thus allows information communication without having to directly observe a visual display. Additionally, if sonification and visual displays are used in conjunction, sonification allows for *multimodal information communication,* in which larger volumes of information can be presented without overloading the visual sense. Because of the fundamental fact that hearing involves listening for changes in patterns over time, sonification makes it easier and more intuitive to notice dynamic patterns.

GOALS OF STUDY

This study seeks to work towards a theory of sonification design and an understanding of the factors that affect the design or use of a sonification. By focusing on ***listener comprehension of sonifications as measured by accuracy of visual replication***, this

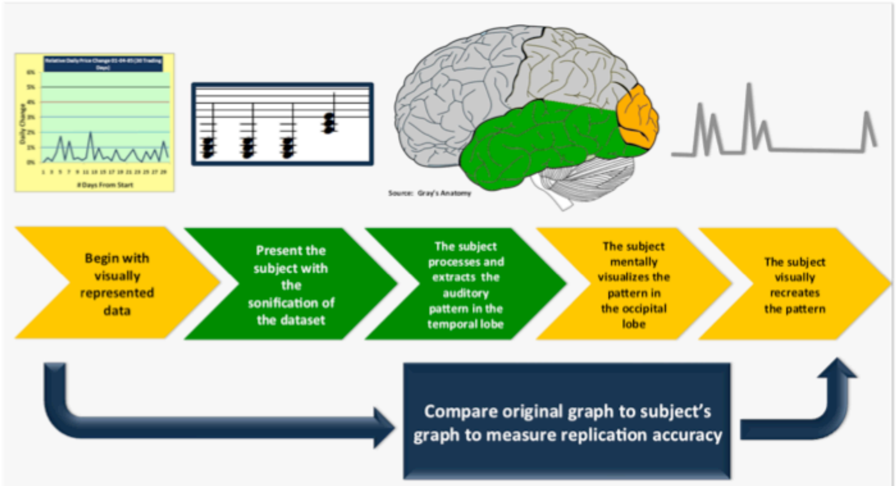

Figure 2. Comprehension Flowchart

study extends the methodologies of cognitive graph comprehension theory to the auditory realm, allowing a novel exploration into the cognitive processes that underlie listener perception of sonifications. In accordance with the overall goal of creating a theory for sonification design, this study aims to identify the factors that drive or ***influence a listener's ability to accurately comprehend and process a sonification***

PROCEDURE OF STUDY

The experiment involved assessing listener comprehension of sonifications by measuring the accuracy with which a listener could visually replicate the pattern contained in a sonification- essentially, how accurately a user could extract a pattern from a sonification and draw this pattern on a visual display.

Design of Study and Metrics Created

In order to collect data, a data collection module was written for an Archos 9 tablet device, which allows for user input and "drawing" using a stylus. Participants were instructed to listen to 12 sonifications and draw a corresponding visual representation (a line graph) as they listened by representing increases in pitch as increases in their visual graph. Each participant was given 3 "training" trials to gain familiarity with the equipment and experimental procedure, followed by 12 "experimental" trials.

A variety of sonifications, all 15 seconds in length and containing the same range of pitches, were created. A subject pool was selected as to span multiple demographic factors, including age, gender, and musical experiences. All subjects were above the age of 18, and were selected from the following populations: seniors at local high schools, teachers at local high schools, students at local universities (primarily the University of Central Florida), and professors and researchers at the University of Central Florida. For each subject, demographic information was collected regarding age, musical experience, prior sonification experience, and hearing and visual impairments.

Subjects were randomly allocated to either an experimental or control group. In order to study the cognitive processes of comprehending a sonification, the study gave subjects a specific cognitive context with which to interpret the sonifications. By giving a user a specific visual template (i.e. x- and y- axes) it is possible to control the visual context in reference to which a sonification is processed, as a subject will interpret the sonification in reference to or in context of these visual features. The control group received all blank screens to draw their visual representations on; thus, they interpreted sonifications in reference to a blank screen. The experimental group, however, received 4 blank screens, 4 screens with x- and y- axes, and 4 screens with axes and discrete grid points; they then interpreted sonifications in reference to each of these visual cognitive contexts. Comparisons between the control and experimental groups could then be used to determine the impact of each of these cognitive references on accuracy of comprehension.

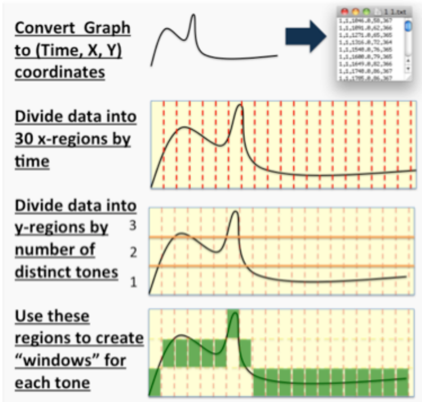

Figure 3. Accuracy Rate Algorithm, using signal detection theory logic

Figure 4. Subject responses to tones were classified as correct (green) or incorrect (red)

In order to quantify the accuracy of a visual representation, cues were taken from signal detection theory to create an algorithm for gauging the accuracy of a listener's perception or replication of a sonification. More information about this algorithm is contained in **Figures 3 and 4**.

Two types of accuracy rates were calculated: the recognition accuracy rate and the magnitude accuracy rate. The recognition accuracy rate measured a subject's accuracy with *recognizing* that a tone was being played as indicated by drawing a peak in the graph. The magnitude accuracy rate, however, assessed the subject's accuracy of indicating that a *specific* tone was being played by drawing a peak of a certain magnitude relative to other peaks in the graph.

Fifty (n=50) subjects were exposed to each of the twelve trials of the experiment. Demographic data covering age, gender, musical experience, hearing impairments and occupation was collected at the conclusion of the experiment. Tests were administered in an individualized setting, with the subject wearing headphones and using an Archos 9 tablet device.

RESULTS OF STUDY

Results indicate that human listeners ***do have the ability to extract and comprehend patterns presented through sonification*** with an overall recognition accuracy rate of ***76%***. Based on there being two possible correct responses (hits) and two possible incorrect responses (misses) for any point in time, the null hypothesis of the study was that the recognition accuracy rate would be no better than the 50% expected through random chance alone. A t-test comparing the experimental accuracy rate to the expected accuracy rate revealed statistically significant results, with a **p-value of 0.0000**.

Results further indicate that listeners can also recognize the exact magnitude of the tone being played, relative to other tones in the sonification. The overall magnitude accuracy rate, which measured the percentage of time that a subject recognized the correct *magnitude* of a tone being played when they did recognize that a tone *was* being played, was **89%**, with a standard deviation of 0.13658. This reveals that when listeners did recognize that a tone was being played, they also recognized the correct relative magnitude of the tone in the overwhelming majority of cases.

Trial	Trial Type	Control Accuracy Rate	Experimental Accuracy Rate	P-value
5	Axis	68.8%	74.4%	0.20
6	Axis	65.77%	69.5%	0.26
7	Axis	80.02%	77.21%	0.25
8	Axis	76.8%	77.3%	0.91
5-8	Axis	72.8%	74.6%	0.38
9	Grid	76.42%	79.96%	0.13
10	Grid	63.6%	72.8%	0.11
11	Grid	93.26%	91.94%	0.39
12	Grid	84.97%	86.36%	0.42
9-12	Grid	79.6%	82.8%	0.15

Figure 5. Experimental vs. Control Groups

Control and Experimental Groups Comparison

In order to study the effect of specific cognitive contexts (based on visual templates) on accuracy rate while correcting for the confounding variable of learning throughout an experiment, subjects in the experimental group were compared to subjects in the control group within each of the 12 trials. These comparisons demonstrate the difference in accuracy rates caused by ***the cognitive framework in which a sonification was processed***. Trials with x- and y- axes had a 75% accuracy rate as compared to the 73% accuracy rate in the corresponding trials without axes; however, this difference was not statistically significant, with a p-value of 0.388. Trials with axes and discrete grid points had an accuracy rate of 83% as compared to the 80% found in corresponding control trials, but once again, this difference was not statistically significant, with a p-value of 0.150. **See Figure 5 for the complete results and p-value summaries.**

The fact that differences in accuracy rate did occur between experimental and control groups indicates that altering the visual framework through which a sonification is processed may produce an discernible effect on accuracy rate. While not statistically significant, these results do indicate the potential of maximizing accuracy of comprehension by training listeners to interpret sonifications in reference to a specific cognitive context.

Demographic Factor	Group 1	Group 1 Accuracy	Group 2	Group 2 Accuracy	P-Value
Age	Age < 35	77.8%	Age > 45	70.5%	0.00
Gender	Male	77.6%	Female	74.5%	0.04
Music Exp.	Yes Music Exp.	77.6%	No Music Exp.	76.8%	0.16

Figure 6. Demographic Factor Summary

Demographic Factors Comparison

Statistically significant differences were found between demographic groups of age and gender. In terms of age, the younger (age < 35 years) group outperformed the older (age > 45 years) group with a p-value of 0.000, just as males outperformed females with a p-value of 0.042. These differences may be due to differences in hearing ability or auditory processing ability between groups, and thus invite further inquiry. **See Figure 6 for the complete results and p-value summaries.**

IMPLICATIONS FOR SIMULATION/TRAINING

This research contributes valuable tools to the simulation and training industry, allowing for increased implementation and understanding of auditory simulations as well as a framework for further exploration into auditory simulation perception. The net effect of such advances is a more immersive simulation that draws heavily from multiple modalities to best emulate and prepare for real life situations.

The first implication of this research for the simulation and training community is a heightened understanding of auditory perception. Large amounts of research have gone into the visual aspect of simulations, improving graphics and rendering processes to heighten realism. However, relatively little research has gone into the auditory side of simulations; while such auditory cues can be a crucial part of a combat scenario, we know little about how to design such auditory simulations based on how they will be perceived. This research examines such auditory pattern perception from an objective aspect, leading to insights about the accuracy and processes of perception. By understanding how a subject will process and extract information from an auditory simulation, as well as the accuracy with which they can be expected to do so and relevant demographic factors in this process, the simulation and training community can now begin to design auditory simulations based on how they are perceived, heightening realism and immersion.

Additionally, the tools developed as part of this research allow for the objective exploration into further aspects of perception. Based on the two step model of comprehension and the algorithms for quantitatively measuring perception accuracy created as a part of this study, it is now possible to experimentally determine subject perception and comprehension of auditory signals. While previous experimental methods relied on knowledge tests, a subjective analysis of perception, these new methods allow for true measurement of perception, increasing the validity of such experiments. This then allows the simulation and training community to quantitatively evaluate the effect and perception of auditory components of simulation, opening an entirely new field of objective experimentation.

PRACTICAL APPLICATIONS

By using a visual replication task to measure accuracy of comprehension, this study has revealed that listener comprehension of sonifications is highly accurate, thus demonstrating that deeper levels of comprehension of sonifications are feasible. A visual replication task, which requires a user to mentally process an entire sonification, can be considered similar to an industry application of sonification. However, rather than demonstrating comprehension through visual replication, an industry application may involve analysis and action based upon the sonification itself. Having demonstrated high rates of comprehension accuracy through visual replication, this study indicates that practical applications of sonification, too, are viable.

Sonification may be advantageous in the following categories of situations:

1. When visual display is not an option: for visually impaired users or soldiers in a combat scenario where looking at a visual display is impossible, sonification could be used to represent data. This would allow visually impaired scientists to navigate a dataset or soldiers to receive time critical information in the field when visual displays aren't present.

2. When a visual display is not accurate enough: because of the low resolution of visual displays in some scenarios, data displayed visually may not be detailed enough to display small changes in data. However, sonifications present no issue of resolution, and can be used to demonstrate changes in data that may otherwise be impossible.

3. When a visual display would be overwhelming: large amounts of data displayed visually can lead to visual overload or visual fatigue. In situations such as stock trading, where large amounts of dynamic data are taken into account to make a decision, such an overload can prevent a user from identifying key patterns or changes in data. Sonification can be used to complement visual displays and increase the bandwidth of data that can be communicated without overloading or fatiguing a user's visual sense.

4. When a visual sense is occupied or not oriented in a certain direction: in scenarios where users are moving around or already using their visual sense, sonification can be used to communicate information without interfering with the primary visual task. This can be used to represent data for drivers or pilots focused on directing their vehicle or for doctors performing a surgery while receiving information on the patient's vital signals through sonification.

5. When visualization isn't suited to the data: visualization represents one cognitive schema to analyze data through, but by using alternate schemas, such as sonification, to display data, previously obscured meaning may be extracted. An example of this is taken from NASA's Voyager project, where data from the spacecraft was obscured by "visual noise" until sonification revealed that the signals were due to micrometeoroids hitting the sensors.

CONCLUSIONS AND RECOMMENDATIONS

People can "see" what they "hear". This research has shown that the human brain can extract, comprehend and translate information presented in audio patterns to visual patterns with a high degree of accuracy, opening the doors to the use of sound as an alternative to visual displays in HCIs.

In conclusion, the null hypothesis was rejected in favor of the alternate hypothesis with a p-value of 0.000 as human subjects were able to visually replicate an auditory pattern with a **76% accuracy rate**, significantly higher than the 50% accuracy rate expected through random chance alone. The difference in accuracy rates between various cognitive contexts has been demonstrated, revealing an increase in accuracy when listeners are exposed to axes or discrete grid points. Furthermore, the effect of relevant demographic factors on accuracy rate has been demonstrated, identifying males and those below 35 as having statistically higher accuracy rates than females and those above 45, respectively.

The protocols and procedures developed as a part of this study have also been proven to be useful and applicable in other studies. By utilizing a two-phase model of comprehension and controlling the visual cognitive context of comprehension, it is possible to quantitatively study sonification comprehension in the same way that eye-tracking studies allow research into visual graph comprehension. Differences in comprehension accuracy rate emerged between various cognitive contexts, with subjects who listened in reference to x- and y- axes and discrete grid points outperforming subjects who listened only in reference to a blank screen. These differences in comprehension accuracy rate by cognitive context indicate that listeners may extract information from a sonification in reference to axes, one of the first insights into the process of sonification comprehension. Since two relevant cognitive contexts have been identified, this study invites further inquiry into other possible cognitive contexts.

As the first study of its kind to apply cognitive graph comprehension theory to the auditory realm, this research has demonstrated the viability of sonification for information communication as well as created novel methods for studying listener perception of sonifications, such as the two-phase model of comprehension and algorithms for assessing accuracy of comprehension. It is the hope of the researcher that these results and methodologies will lead to further research seeking to revolutionize HCIs through sonification.

ACKNOWLEDGEMENTS

The authors would like to thank the entire Institute for Simulation and Training at the University of Central Florida for its assistance, with particular acknowledgement to the Media Convergence Laboratory, Dr. Charles E. Hughes, and Dr. Stephen M. Fiore.

REFERENCES

Baars, Bernard J., Banks, William P. & Newman, James B. (2003). Essential Sources in The Scientific Study Of Consciousness. The MIT Press.

Bly, S. (1982). Sound And Computer Information Presentation - Doctoral Dissertation. University Of California, Davis, California.

Brewster, Stephen A. (1996). A Sonically Enhanced User Interface Toolkit. Proceedings of the International Conference On Auditory Display.

Chambers, J. M., Matthews, M. V., & Monroe F. R. (1974). Auditory Data Inspection. Technical Report. AT&T Bell Laboratories, Murray Hill, New Jersey.

Chang, Irene & Boulanger, Pierre (2005). A 3D Perceptual Metric Using Just-Noticeable Difference. Eurographics. 97-100.

Hermann, Thomas (2002). Sonification for Exploratory Data Analysis - Doctoral Dissertation. Neuroinformatics Group, Bielefeld University, Germany.

Hermann, T. & Ritter, H. (1999). Listen To Your Data: Model-Based Sonification For Data Analysis. Int. Inst. For Advanced Studies In System Research And Cybernetics. 189-194.

Kramer, Gregory (1994). An Introduction to Auditory Display. Auditory Display, G. Kramer Ed., International Conference on Auditory Display. pp. 1-79.

Kramer, Gregory et. al. (1997). Sonification Report: Status of The Field And Research Agenda. National Science Foundation.

Levintin, Daniel P. & Cook, Perry R. (1996). Memory For Musical Tempo: Additional Evidence That Auditory Memory Is Absolute. Jour. Perception and Psychophysics 58. pp. 927-935.

Lodha, Suresh K., Wilson, Catherine M., & Sheehan, Robert E. (1996). Listen: Sounding Uncertainty Visualization. Proceedings Of The 7Th Conference On Visualization. pp. 189-195.

Minghim, R., & Forrest, A.R. (1995). An Illustrated Analysis Of Sonification For Scientific Visualization. Proceedings of The 6th IEEE Visualization Conference (Visualization '95). pp. 110-117.

National Aeronautics & Space Administration, Goddard Space Center (2006). Xsonify . Goddard Space Flight Center Space Physics Data Facility. http://spdf.gsfc.nasa.gov/research/sonification/documents/Alltogether.pdf.

Nesbitt, Keith V. (2001). Modeling The Multi-Sensory Design Space. Proceedings of The 2001 Asia-Pacific Symposium On Information Visualization, Volume 9. pp.27-36.

Patel, Neel S., & Hughes, Darin E. (2010). A Listener Comprehension and Reaction Time Study of Sonification. Proceedings of The 2010 Interservice/Industry Training, Simulation & Education Conference (I/ITSEC).

Pollack, I. & Ficks, L. (1954). Information Of Elementary Multidimensional Auditory Display. Journal Of Acoustic Soc Amer 36. pp. 155-158.

Recordare Inc. (2008). Musicxml 2.0. Tutorial. ;

Smith, Steven W. (1997). The Scientist And Engineer's Guide To Digital Signal Processing. California Technical Publishing. chap. 22.

Song, Hong Jun (2008). Aesthetic And Auditory Enhancements For Multi-Stream Information Sonification. 3Rd International Conference On Digital Interactive Media In Entertainment And Arts. pp. 224-231.

Speeth, Sheridan (1961). Seismometer Sounds. Journal Of Acoust Soc Amer 33. pp. 909-916.

Thomas, Kim (May 2007). Just Noticeable Difference and Tempo Change. Jour. Of Scientific Psychology. pp. 14-20.

Walker, Bruce N. (Sept. 2000). Magnitude Estimation Of Conceptual Data Dimensions For Use In Sonification - Doctoral Dissertation. Rice University, Houston, Texas.

Walker, Bruce N., Lindsay, Jeffrey, & Godfrey, Justin (2004). The Audio Abacus: Representing Numerical Values With Nonspeech Sound For The Visually Impaired. The Tenth International Conference On Auditory Display.

Walker, Bruce N., & Kramer, Gregory (Oct. 2005). Mappings And Metaphors In Auditory Displays: An Experimental Assessment. ACM Trans. On Applied Percep., Vol 2 No. 4. pp. 407-412.