# AN AGENDA FOR RESEARCH AND DEVELOPMENT OF MULTIMODAL GRAPHS

*Bruce N. Walker and Michael A. Nees*

Sonification Lab
School of Psychology
Georgia Institute of Technology
654 Cherry Street NW
Atlanta, GA, USA 30332-0170
bruce.walker@psych.gatech.edu, gtg673z@mail.gatech.edu

**ABSTRACT**

Effective multimodal graphing tools can be beneficial to both sighted and visually impaired students and scientists. However, before this can become a reality, considerable research is required on the auditory graphing components. We suggest mappings, polarities, scaling, context, and training be studied in particular. We point to previous work in these areas and make suggestions for expanded research questions. We recommend that more complex and realistic data sets be used, and that visually impaired participants play a larger role in the research. The design of multimodal graphing software should be informed by empirical findings. Effective research and useful software tools will bring a broader perspective to data analysis for all who use graphs, regardless of visual ability.

## 1. INTRODUCTION

Science and science education are now a thoroughly collaborative process. Being able to examine and interpret quantitative data individually, and discuss them with others, is crucial to the creative and analytic process. This, in turn, is predicated on the availability of useful and usable tools for creating data displays that can be employed both by individuals and teams. Unfortunately, for the visually impaired there are few data display tools that are effective to the same degree as visual displays are for their sighted colleagues. This seriously impedes the interpretation of data by blind individuals and prevents their involvement in teamwork or collaborations.

The use of sound for graphs has considerable potential, having been implemented in software such as Triangle [1], the Accessible Graphing Calculator (AGC) [2], the Math Description Engine (MDE) Graphing Calculator [3], the vOIce Accessible Graphing Calculator [4], and the Sonification Sandbox [5, 6]. However, there has been very limited *systematic* study of how, exactly, to create effective auditory graphs, so it is not surprising that the effectiveness of most of these applications could be dramatically improved. Only with an expanded, solid foundation of empirical research can a truly effective software application be developed. Such research needs to include several specific areas, outlined below.

The next step, developing effective software for *simultaneously* producing visual and auditory graphs, will allow individuals and teams to interpret the data in the manner they prefer (or require), and have a shared representation to support collaborative discussions. We contend that both sighted and visually impaired students and scientists can make use of the auditory display of quantitative information, so long as the displays are sophisticated and well designed, the listeners are trained, and the designer is aware of any differences that may exist in how the various listeners tend to interpret what they hear. Thus, a multimodal display will have significant impact, especially when its use is extended outside the classroom or lab, on creating more universally accessible documents, web sites, and other published data.

### 1.1. Using Graphs for Data Analysis Tasks

*Trend analysis* involves observing the local shape and contour of the graph to determine if the data values are increasing or decreasing [7, 8]. This can help the user determine, for example, if the temperature is rising or falling. *Pattern detection* and *pattern recognition* make use of the more global contour to determine if the data follows a particular pattern, such as a Gaussian curve or sinusoidal cycle. More advanced tasks include *point estimation*, where the user must determine the specific “y” value corresponding to a given “x” value, such as the temperature on a certain day, given a year’s worth of data points. It involves several perceptual and cognitive subtasks including interpolation and magnitude estimation, discussed later. *Point comparison* involves doing this task twice, and comparing the two resulting estimated values. Both trend analysis and point estimation tasks are required in nearly all real data analyses, and are important skills for students and scientists alike. While most trend analysis is quite easy, point estimation is quite challenging with a visual graph, even for an experienced user.

Regarding experience, visual displays of quantitative information are pervasive (Jones [9] calculated that 2.2 trillion graphs were published in 1994 alone), and the average user has many years of both formal and informal instruction with visual displays. Relatively speaking, much is known about how to design visual graphs for optimal effectiveness (e.g., [10, 11]). In contrast, the field of auditory graphs is still quite new, which leads to the following challenges: 1) there are few auditory graphs in regular use; 2) the auditory graphs that are in use have not been studied to determine optimal design approaches [12]; and 3) people have little experience and no training in how to interpret auditory graphs. As a result, point estimation and the more sophisticated analysis tasks are simply *impossible* with nearly every auditory graph that has been implemented to date. This is not because tools to support these tasks cannot be made, but because we seem to still be in the Stone Age of auditory graph design. Before any truly effective multimodal display tool can be implemented to the benefit of both sighted and visually impaired users, more fundamental research needs to examine the auditory display component.

### 1.2. Lack of Sophistication in Auditory Displays

There have certainly been plenty of studies demonstrating that sound and sonification *can* be an excellent way to examine data—especially complex, multidimensional, and time-varying data—regardless of one's visual abilities (see, e.g., [12, 13]). An early study of even simple auditory representations of data found them to be comparable in efficacy to the tactile displays traditionally used to present quantitative information to the blind [14]. Flowers and Hauer [15] demonstrated that participants categorize groups of visual graphs and their auditory counterparts along the same dimensions of shape, slope, and degree of linearity. Flowers, Buhman, and Turnage [16] found further evidence for the equivalence of auditory and visual presentations of scatterplots. Participants estimated the same Pearson correlation *r* value for visual scatterplots and the corresponding auditory displays. Bonebright, Nees, Connerley, and McCain [17] found similarly encouraging results regarding matching auditory graphs and their visual counterparts. However, more sophisticated tasks, such as point estimation or comparison, require more sophisticated auditory displays, and we need more research before the accomplishment of those tasks can become a reality.

Let us consider for a moment exactly how auditory graphs have typically been implemented: a simple "tone graph" wherein changes in data values drive changes in the pitch of a simple sound (granted, some data *sonifications* have been much more sophisticated, but also share many of the problems of simpler auditory graphs). This display methodology, oversimplified to a fault, is not due to any inherent limitations in the display technology or the ability of the listener to process it. The amount of information that can be simultaneously displayed via sound is remarkable. Levitin [18] proposed *seven* distinct perceptual dimensions of music, each of which can be independently manipulated. Pitch is only one of them. Furthermore, researchers have provided evidence that particular properties of complex non-speech sounds can be isolated and assigned differing degrees of perceptual importance (e.g., [19-21]). Kramer has sonified up to nine dimensions of data in a single sonification [22]. Thus, it is abundantly clear that the typical "tone graph" dramatically underutilizes the data processing and pattern recognition capabilities of the human auditory system.

Beyond underutilizing our auditory capabilities, tone graphs are poorly designed for the intended tasks. As Walker points out [7, 8], with these overly simple displays there is little information available to put the tones into some kind of context. This is equivalent to developing a visual "graph" like the one depicted in Figure 1. Visual graphs rely upon legends, tick marks, labels, and symbols (i.e., the visual *context*) to provide necessary information about data portrayed in the display [23]. Without context the data are not interpretable. It is just not a graph without the context. One could never determine how much change in temperature there had been, or what the temperature was on a particular date, or even that this data had anything to do with temperature. Furthermore, a lack of context prevents users from discussing the data in any meaningful way. Likewise, auditory graphs require contextual cues to be effective in supporting even the most basic interpretation tasks. Simple trend analysis is impossible in the absence of context, because there is nothing to indicate whether an increase in the pitch means an increase or decrease in the data. The lack of any scaling cues means that the there is no way to determine what change in the data is represented by, say, a doubling of pitch.

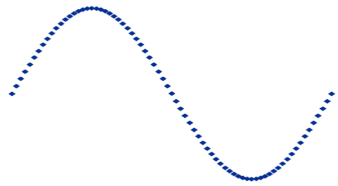

**Figure 1.** "Graph" lacking all context such as axes, tick marks, and legends. Similarly impoverished auditory graphs turn their listeners into second-class citizens in the scientific enterprise.

Thus, as we noted earlier, point estimation is simply impossible with tone graphs. Unfortunately, even some recent auditory graph design recommendations have surprisingly made no mention of auditory context (e.g., [24]). Information-impoverished auditory graphs turn their listeners into second-class citizens in the scientific enterprise.

To unlock the full potential of auditory graphs, and to enable them to become truly effective scientific tools, there remains a great need for more basic science in auditory graph design. Only recently has there been any systematic investigation into what information is required in an auditory graph, and how to provide it with sound (e.g., [7, 8, 15, 17, 24]). To be able to implement sophisticated, effective auditory graphs that allow similar data extraction and interpretation as visual displays, auditory context will need to be more fully understood.

## 2. AREAS FOR FOCUSED RESEARCH

### 2.1. Mappings, Scalings, and Polarities

While there has been very little research explicitly studying auditory graph design, we can learn from the more general field of sonification, where the available display dimensions are sound parameters such as frequency (pitch), amplitude (loudness), timbre, and tempo, among others [18, 25, 26]. An important issue is the best *mapping* of data values to the available display (sound) dimensions. While pitch is the most commonly used dimension, Walker has pointed out that different sound dimensions are better for representing certain data types. For example, pitch is better for representing temperature, but tempo may be better for size [8, 26, 27]. Next, given a specific mapping, sonification design then requires the selection of polarities and scalings. *Polarity* refers to how the data dimension and the display dimension co-vary. If a data dimension (e.g., temperature) increases, a positive polarity would dictate that such a change be represented by a corresponding increase in the assigned display dimension (e.g., increasing pitch). A negative polarity would dictate that such a change be represented by a corresponding decrease in the assigned display dimension. Lastly, *scaling* refers to how much change in a data dimension is represented by a given change in the display dimension. The "best" scaling value for representing data with sound can depend on the exact type of data and display dimensions in use (e.g., [8, 27-30]). This means that there will be different scaling factors for, say, dollars, temperature, and urgency, when mapping onto pitch. The use of the most preferred parameters should, overall, lead to better performance with a sonification or auditory display [8, 31]. Thus, more research is needed in how to map data dimensions onto sound dimensions, and assumptions regarding mappings, scalings, and polarities should not be made by auditory graphs designers in the absence of evidence.

### 2.2. Context in Auditory Graphs

Even auditory displays that make optimal use of mappings, polarities, and scaling factors are not truly auditory graphs until they have contextual cues equivalent to axes, tick marks and labels, so the listener knows what the designer intended. Our recent work [7, Study 1] has shown that even for rudimentary auditory graphs, the addition of some kinds of context cues can provide useful information to users of the display. For example, simply adding a series of clicks to the display can help the listener keep track of the time better, which keeps their interpretation the graph values more "in phase". While this is not an entirely new approach (e.g., [1, 16, 17]), it had not been studied explicitly for its effectiveness. Smith and Walker [7] showed that when the clicks played at a rate that was twice the rate of the sounds representing the data, the two sources of information combined like the major and minor tick marks on the x-axis of a visual graph. Similarly, that same study [7] found that the addition of a repeating reference tone that signified a known data value (in this case the maximum value of the data set) provided dramatic improvements in the attempts by listeners to estimate exact data values. On the other hand, a reference tone that signified the starting value of the data did not improve performance. Thus, it is clear that adding context cues to auditory graphs can play the role that x- and y-axes play in visual graphs, but not all implementations are equally successful.

There are countless ways one could design such context cues, and many more need to be evaluated. For example, we have considered that changing the loudness of the clicks and reference tones may alter their effectiveness by changing the relative salience of the data sounds and the context sounds. More subtle click tracks or reference tones may be more effective than "bold" (i.e., loud) sounds if they can provide the same timing and scaling information while at the same time making it more clear which sounds are "foreground" data sounds and which are "background" context cues. We have only scratched the surface of possible context cues and their configurations, and we need to implement and validate other, perhaps more effective, methods.

### 2.3. Training in Auditory Graph Interpretation Tasks

Once we have determined more effective design approaches through systematic investigations, listeners may still not automatically know how to interpret the resulting auditory graphs. Even if x-axis and y-axis auditory context cues are available, the listener needs to learn what they represent, how to listen for them, and then how to use the information they convey to help interpret the main data series in the auditory graph. Determining the value of a specific data point requires the listener to execute several perceptual, cognitive, and working memory tasks, which map onto to the established Mixed Arithmetic-Perceptual model of comprehension in visual graphs [32]. It has been pointed out that most students and scientists obtain many years of experience and explicit instruction in interpreting visual graphs. Although researchers have mentioned the importance of studying training for auditory displays as well (e.g., [8, 12, 14, 17]), empirical investigations of training for auditory displays remain largely absent in the literature. Much is known about training in general, but it has simply not been applied to bridging the experience gap for listeners and auditory graphs. Even the basics of how best to approach training for auditory graph comprehension is still debatable. Smith and Walker [7] broke the task down into component subtasks for successful training. On the other hand, Walker and Nees [33] have recently looked at alternatives, and found that practice with feedback led to even greater improvements. Thus, there is a need to study context and training in the use of auditory graphs for the interpretation of scientific data, especially given some of the very recent findings in this area (e.g, [7, 33]).

### 2.4. Context and Training with Visually Impaired Participants

The research to date involving context in the design of auditory graphs has nearly exclusively involved sighted participants. However, Walker and Lane [34] have shown that while there are many similarities, there are important differences between how sighted and visually impaired listeners interpret auditory displays. Thus, it remains crucial to extend these context studies to visually impaired participants. Further, we are not aware of any studies at all that have specifically examined different ways to train visually impaired listeners to make use of and interpret auditory graphs. This is somewhat surprising, considering the interest in implementing auditory presentations of data. Presumably there will be many similarities in terms of the benefits of educating the listeners about the components of the auditory graph, as was done by Smith and Walker [7]. However, the other types of perceptual training (e.g., [33]) may have different levels of effectiveness with visually impaired listeners, considering their typically more extensive experience with analytic types of listening. Thus, research needs to include both sighted and visually impaired participants in order to investigate these issues, and display designers should not assume that the best training techniques for sighted listeners will suffice for visually impaired users

### 2.5. Complexity of Data in Auditory Graphs

Almost all of the studies of auditory displays of quantitative information have involved very simplistic data sets, following basic and highly predictable patterns like parabolas and sinusoids (e.g., [7, 15]). While it is important to understand these kinds of data sets very well, given that they are common in many science applications, it is important to also branch out and study data sets that are progressively more complex. The eventual utility of auditory displays, alone or in combination with visual graphs, will depend on how far the auditory representations can go when complex data sets are involved. To this end, increased data complexity and real quantitative data sets (e.g., [17]) need to be examined in empirical studies.

## 3. SOFTWARE REQUIREMENTS

A well-designed software package will allow for the creation of visual and audio data representations for both educational and informative purposes. The recommended research into auditory graphing techniques will feed into more effective software tools for creating useful data displays. As discussed, there are several auditory graphing (and plenty of sonification) software tools available. However, they have either limited utility, or limited distribution. To overcome these issues, we suggest some attributes that the ideal software package should possess. Of course, this is really just a starting point for discussion, and the specific requirements of any software package need to be determined by a careful analysis of the intended users and tasks. Having said that… First, the software needs to be cross-platform, widely available, either free or close to it. It needs to be supported technically, and continually updated, and accessible to, and by, the visually impaired. The software should support the *simultaneous* production of both visual and auditory graphs, both of which need to be designed based on the best practices, which could be substantially informed by the results of research such as that called for here. There must be support for a variety of context cues. Furthermore, training and a solid help system with plenty of examples are crucial (we like the Matlab Help system, as an example of good user support).

## 4. SUMMARY

It is time to take a quantum leap out of the auditory display “Stone Age”, and into the modern era of sophisticated, effective auditory displays of quantitative information. Only then can we begin to understand how to use auditory and visual graphs in a combined manner to enhance data understanding (i.e., interpretation of data for the purpose of discovery or learning) and subsequent collaboration (i.e., the communicative role of graphs). This alone is not sufficient, however. We contend that there has also been a lack of training available in both the creation and interpretation of auditory graphs and their use alongside other data displays. Granted, part of this stems from the prevailing overly simplistic view of how sounds may be used to represent data. Training from both top-down (teacher or other graph creator) and bottom-up (student or other graph consumer) perspectives is crucial.

While research in this field will advance an application area potentially benefiting millions of people with vision loss, it will also lead to a better understanding of auditory presentation of quantitative information in conjunction with other modalities. If auditory + visual graphing systems are developed to be appealing to both the sighted and visually impaired populations—a tenet of Universal Design—everyone wins. Effective tools will provide publishers and Web designers inexperienced in accessible data displays with the tools and training to make their information available to all. There really will be no more excuse for *not* doing so, and in an effective and standardized way as well.

## 5. REFERENCES

[1] J. A. Gardner, R. Lundquist, and S. Sahyun, "TRIANGLE: A practical application of non-speech audio for imparting information.," presented at International Conference on Auditory Display, San Francisco, CA, 1996.

[2] J. A. Gardner, "The Accessible Graphing Calculator: A Self-voicing Graphing Scientific Calculator for Windows," vol. 2004, 1999, pp. Web page for the Accessible Graphing Calculator from DOTS.

[3] NASA Information Access Lab, "NASA LTP Information Access Lab: MDE Graphing Calculator Demonstration (Beta 2.0)," vol. 2004, 2004, pp. Web page.

[4] P. Meijer, "The vOICe Accessible Graphing Calculator," vol. 2004, 2004, pp. Web page for the vOIce Accessible Graphing Calculator for the Blind.

[5] B. N. Walker and M. Lowey, "Sonification Sandbox: A graphical toolkit for auditory graphs," presented at Rehabilitation Engineering & Assistive Technology Society of America (RESNA) 27th International Conference, Orlando, FL, 2004.

[6] B. N. Walker and J. T. Cothran, "Sonification Sandbox: A graphical toolkit for auditory graphs," presented at Ninth International Conference on Auditory Display (ICAD2003), Boston, MA, 2003.

[7] D. R. Smith and B. N. Walker, "Effects of auditory context cues and training on performance of a point estimation sonification task," *Applied Cognitive Psychology*, in press.

[8] B. N. Walker, "Magnitude estimation of conceptual data dimensions for use in sonification," *Journal of Experimental Psychology: Applied*, vol. 8, pp. 211-221, 2002.

[9] R. W. Jones and I. E. Careras, "The empirical investigation of factors affecting graphical visualization," *Behavior Research Methods, Instruments, & Computers*, vol. 28, pp. 643-655, 1996.

[10] J. Bertin, *Graphics and graphic information processing*. Berlin: Walter de Gruyter, 1981.

[11] E. R. Tufte, *The visual display of quantitative information*, 2nd ed. Cheshire, Conn.: Graphics Press, 2001.

[12] G. Kramer, B. N. Walker, T. Bonebright, P. Cook, J. Flowers, N. Miner, J. G. Neuhoff, R. Bargar, S. Barrass, J. Berger, G. Evreinov, W. T. Fitch, M. Gröhn, S. Handel, H. Kaper, H. Levkowitz, S. Lodha, B. Shinn-Cunningham, M. Simoni, and S. Tipei, "The Sonification Report: Status of the Field and Research Agenda. Report prepared for the National Science Foundation by members of the International Community for Auditory Display," International Community for Auditory Display (ICAD), Santa Fe, NM 1999.

[13] W. T. Fitch and G. Kramer, "Sonifying the body electric: Superiority of an auditory over a visual display in a complex, multi-variate system," in *Auditory display: sonification, audification, and auditory interfaces*, G. Kramer, Ed. Reading, MA: Addison-Wesley, 1994, pp. 307-326.

[14] D. L. Mansur, M. M. Blattner, and K. I. Joy, "Sound graphs: A numerical data analysis method for the blind.," *Journal of Medical Systems*, vol. 9, pp. 163-174, 1985.

[15] J. H. Flowers and T. A. Hauer, "Musical versus visual graphs: Cross-modal equivalence in perception of time series data.," *Human Factors*, vol. 37, pp. 553-569, 1995.

[16] J. H. Flowers, D. C. Buhman, and K. D. Turnage, "Cross-modal equivalence of visual and auditory scatterplots for exploring bivariate data samples.," *Human Factors*, vol. 39, pp. 341-351, 1997.

[17] T. L. Bonebright, M. A. Nees, T. T. Connerley, and G. R. McCain, "Testing the effectiveness of sonified graphs for education: A programmatic research project," presented at International Conference on Auditory Display, Espoo, Finland, 2001.

[18] D. J. Levitin, "Memory for musical attributes," in *Foundations of cognitive psychology: Core readings*, D. J. Levitin, Ed. Cambridge, MA: MIT Press, 2002, pp. 295-310.

[19] B. Carroll-Phelan and P. J. Hampton, "Multiple components of the perception of musical sequences: A cognitive neuroscience analysis and some implications for auditory imagery," *Musical Perception*, vol. 13, pp. 517-561, 1996.

[20] J. H. Howard and J. A. Ballas, "Perception of simulated propeller cavitation," *Human Factors*, vol. 25, pp. 643-655, 1983.

[21] S. M. Williams, "Perceptual principles in sound grouping," in *Auditory display: Sonification, audification, and auditory interfaces*, G. Kramer, Ed. Reading, MA: Addison Wesley, 1994, pp. 95-125.

[22] G. Kramer and S. Ellison, "Audification: The use of sound to display multivariate data," presented at International Computer Music Conference, San Francisco, CA, 1991.

[23] P. A. Carpenter and P. Shah, "A model of the perceptual and conceptual processes in graph comprehension," *Journal of Experimental Psychology: Applied*, vol. 4, pp. 75-100, 1998.

[24] L. M. Brown, S. A. Brewster, R. Ramloll, M. Burton, and B. Riedel, "Design Guidelines for Audio Presentation of

Graphs and Tables," presented at International Conference on Auditory Display ICAD2003, Boston, MA, 2003.

[25] S. Carlile, "An overview of auditory dimensions that can be used to represent information.," presented at International Conference on Auditory Display, Kyoto, Japan, 2002.

[26] B. N. Walker and G. Kramer, "Mappings and metaphors in auditory displays: an experimental assessment," presented at 3rd International Conference on Auditory Display (ICAD96), Palo Alto, CA, 1996.

[27] B. N. Walker, "Consistency of magnitude estimations with conceptual data dimensions used for sonification," in *Perception & Psychophysics*, 2005.

[28] J. Edworthy, S. Loxley, and I. Dennis, "Improving auditory warning design: Relationship between warning sound parameters and perceived urgency," *Human Factors*, vol. 33, pp. 205-231, 1991.

[29] J. Edworthy, E. J. Hellier, and R. Hards, "The semantic associations of acoustic parameters commonly used in the design of auditory information and warning signals.," *Ergonomics*, vol. 38, pp. 2341-2361, 1995.

[30] E. Hellier, J. Edworthy, B. Weedon, K. Walters, and A. Adams, "The perceived urgency of speech warnings: Semantics versus acoustics," *Human Factors*, vol. 44, pp. 1-17, 2002.

[31] J. G. Neuhoff and J. Wayand, "Pitch change, sonification, and musical expertise: Which way is up?" presented at International Conference on Auditory Display (ICAD2002), Kyoto, Japan, 2002.

[32] D. J. Gillan and R. Lewis, "A componential model of human interaction with graphs: I. Linear regression modeling," *Human Factors*, vol. 36, pp. 419-440, 1994.

[33] B. N. Walker and M. A. Nees, "Brief training for performance of a point estimation sonification task," presented at Eleventh International Conference on Auditory Display (ICAD2005), Limerick, Ireland, 2005.

[34] B. N. Walker and D. M. Lane, "Psychophysical scaling of sonification mappings: A comparison of visually impaired and sighted listeners," presented at 7th International Conference on Auditory Display (ICAD2001), Espoo, Finland, 2001.