10-2005

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Published in *ACM Transactions on Applied Perception* 2:4 (October 2005), pp. 473–476. http://doi.acm.org/10.1145/1101530.1101545

Submitted March 2005; revised June 2005; accepted July 2005.

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Abstract
Sonification tools have not yet become typical components of data analysis software, despite dramatic advances in sound-production capabilities of personal computers over the past decade. However, we continue to believe that auditory displays have the potential to be highly useful for "small scale" exploration of data for normally sighted users as well as an alternative format for users with visual impairment. Demonstration of effective examples of auditory data displays and design of *flexible* software tools for data sonification will be key factors in determining the impact of this method of data representation.

Keywords: sonification, auditory display, data mapping, experimentation, human factors, performance

1. Historical Context

Our initial interest in auditory data sonification was stimulated by frustration with existing technology for assisting blind students in learning elementary statistics. Tactile analogs of histograms of probability density functions, histograms, and, especially, bivariate scatterplots were time consuming to produce and were reported to be cumbersome to use, even for very skilled Braille readers who had experience using other types of raised-line graph analogies. Inspiration for experimenting with auditory display alternatives came from sharing this issue with members of a bluegrass band (UNL faculty and graduate students) in which the first author was participating at the time. A discussion of this topic with students in an undergraduate perception class caught the interests of an undergraduate, Terry Hauer [Flowers and Hauer, 1992, 1993, 1995] and eventually attracted interest from the other co-authors of the 1996 ICAD presentation [Flowers, Buhman, and Turnage, 1996], who were then UNL Psychology graduate students.

2. Research Process

While our initial motivation to explore perception of auditory data displays came from assistive technology needs, lack of sufficient numbers of visually impaired and blind participants precluded research specifically directed at that population. However, experimentation with auditory displays using normally sighted participants indicated to us that data features, such as distribution shape and spread [Flowers and Hauer, 1992,1993], function shape [Flowers and Hauer, 1995], and scatterplot properties [Flowers, Buhman, and Turnage, 1997] could be extremely well conveyed to normally sighted users through sonification, after quite minimal practice.

In particular, our work with auditory scatterplots suggested that the ears could pick up bivariate distributional properties, such as outlier patterns, variations in the point density or "gaps" in the point cloud (i.e., homoscedasticity violations), and even differences in data quantizing (i.e., rounding) that were not at all apparent from visual displays. Our work with these "simple" datasets contrasted quite strongly with what was then a dominant theme in many of the early ICAD meetings—the use of quite complex auditory displays, often generated by highly specialized audio synthesis, in order to render complex multivariate data. Given our observation that sound production capabilities of personal computers was undergoing rapid development during the mid-1990s, we felt it was timely to offer a position paper reflecting our views about the potential use of personal "small-scale" sonification at the 1996 ICAD meeting.

3. Body of Work

Since the presentation of our 1996 paper at ICAD, there has been an increase in the proportion of ICAD presentations dealing with sonification of small-scale data sets using conventional desktop computers for a variety of applications. This trend is most likely not a direct result of our position paper, but a consequence of hardware developments that have made a wider variety of auditory display research accessible to individual investigators lacking access to specialized audio synthesizers or supercomputer facilities. However, there are several themes suggested in the 1996 paper that continue to influence work from our laboratory, and work by others.

One line of ongoing research in our laboratory has focused on sonification of relatively "low-density" multivariate time series data, such as weather observations [Flowers, Whitwer, Grafel, and Kotan, 2001; Flowers and Grafel, 2002]. Such datasets appear well adapted to sonification, since they are sequential in nature, and combine both discrete events (e.g., precipitation events, storms) with continuous data (e.g., daily temperature). Our work in this area continues to examine perceptual grouping effects and auditory attention limits that constrain the number of streams that should be simultaneously presented, as well as issues of sensory and working memory that affect the optimal display durations for a given task.

Other investigators continue to work on themes presented in our 1996 paper, primarily in two areas— the optimization of particular classes of simple displays for data summary, and the development of software tools that allow experimentation with sonification. Space constraints preclude a complete review of these, but examples of research on the first of these themes include ongoing projects by Walker and his colleagues to investigate (and optimize) actual quantitative estimates derived from auditory function graphs [e.g.,Walker, 2002], related work on auditory line graph optimization [Brown, Brewster, Ramloll, Burton, and Reidel, 2003], and exploration of auditory representation of distribution properties [Peres and Lane, 2003]. Examples of tools for experimentation with sonification on desktop computers have been developed by Walker and Cothran [2003] and by Brown, Brewster, Ramloll, Reidel and Yu [2002].

4. Relations to the Field of Auditory Display

Our program of research has encountered challenges from sometimes unforeseen limitations of human attention, memory, and perceptual interactions. In this regard it has a great deal in common with other auditory display applications. It is also becoming clear that display methods that "work well" in a domain, such as describing simple numeric functions in an auditory graph, can be applied to design of auditory on-line monitoring of equipment or vehicles [e.g., Edworthy, Hellier, and Aldrich, 2003]. Continuing to share research experiences with investigators studying quite different auditory display applications, at forums such as ICAD, is thus extremely valuable. It is essential, however, to recognize that current and envisioned applications of auditory display technology cover an extremely diverse range of activities, with differing task demands. The type of information needed by an anesthesiologist monitoring an auditory display "in the background" during surgery is very different from the type of information needed by either a climate researcher making comparisons of monthly precipitation and temperature acquired from different historical periods, or a blind high school student who is learning about shapes and roots of polynomial functions. Even within the limited range of "data exploration from the desktop," issues such as the importance of detecting specific values of a variable versus having an overview of patterns of change among several variables, will differ greatly from application to application.

5. Future Work

There are two major implications of the wide diversity of tasks for which sonification is likely to be used. The first is that it may prove impractical to establish design guidelines for auditory displays unless such guidelines are restricted to a quite narrow range of applications. The second (one that directly impacts needed future work) is that the development of display design software tools will need to incorporate more data-to-sound mapping and editing flexibility than is present in existing software prototypes (for example, the ability to control the speed or pitch values in an ongoing *pattern* of notes or sounds, and the ability to edit auditory displays by "pasting" or deleting auditory events and specific temporal locations). This latter concern is by no means unique to sonification, as most of us have experienced frustration with what *cannot* be done with supposedly "state-of the art" software for *visually* graphing data.

One important research area that could impact a wide variety of sonification applications is *expertise.* With the possible exceptions of early sonar research and some current work in medical systems monitoring, little research has explored effects of extensive practice on perception of non-speech auditory displays. Based upon well known changes in comprehension rates for Morse code, and compressed voice recognition by skilled users of JAWS [Freedom Scientific, 2005] and similar software, it is reasonable that substantial performance changes will occur with extensive experience in use of data sonification. However, auditory perception of data features is very different from translating text from Morse code or compressed phonemes. Only additional research can reveal the extent to which practice will impact preferred rates of auditory data perception and the number of streams of data that can be included in a display without performance losses.

6. Concluding Thoughts

Data sonification remains a topic that is still unfamiliar to researchers who could potentially benefit from its development, even though recent innovations in personal computer hardware make auditory data display possible for a wide range of users. When or whether sonification becomes a standard part of data analysis software may depend upon one or more "key discoveries" for which sonification, as opposed to visualization or numerical modeling, provided the critical insight. Continued pursuit of "problem-oriented" research in sonification that includes collaboration between cognitive scientists with interests in auditory perception and researchers who have the data exploration needs will increase the probability of such discoveries.

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