

Evaluating the Effectiveness of Auditory and Tactile Surface Graphs for the Visually Impaired

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Abstract

Graphs of numerical data allow the representation and communication of quantitative relationships in many important fields. We have developed an accessible graphics system that allows people with visual impairments to create and explore auditory and tactile graphs of multivariate datasets that are typically represented as 2D colormaps or 3D surface graphs. In this paper we describe an experiment conducted with both visually impaired and sighted (but blindfolded) users, to evaluate how effectively auditory and tactile graphs produced by the system convey the amplitudes and widths of 3D Gaussian surfaces. With respect to discriminating surface amplitudes, the users showed no significant differences in performance using either the auditory or tactile graphs. With respect to discriminating surface widths, performance was significantly better with the tactile graphs than with the auditory graphs. Both user groups performed similarly, showing no significant differences in error rates or discrimination abilities. Finally we found an effect of surface data range on performance, with higher error rates for graphs of higher or wider surfaces. The results of these studies provide insights into performance and usability that should allow developers to create more effective accessible graphics systems.

Introduction

Graphs of numerical data provide visual representations of quantitative relationships in the world around us. Graphs are essential tools for analysis, discovery, and communication in science, mathematics, engineering, and many other fields. Unfortunately, standard visual graphs are largely inaccessible to people with visual impairments. To address this problem researchers have been working to create *accessible graphics systems* that make graphical information available to the visually impaired.

We have developed an accessible graphics system called IVEO that incorporates an embossing color printer, a touch tablet, and a multimedia computer. Through custom software, users can create multimodal graphs that can include visual, tactile, and auditory data representations. Users print visual/tactile graphs on the embossing printer, and then explore them on the touch tablet, where the software provides coordinated audio content. While the IVEO system has been quite useful for improving access to discrete, object-oriented graphs such as technical diagrams and GIS maps [1], visually impaired users also need to be able to access graphs of continuous multivariate datasets (often visualized as color maps or 3D surface plots). Therefore we have developed extensions to this system that allow the creation of tactile and auditory graphs of multivariate data. In this paper, we describe an experiment that tests the effectiveness of this system.

Related Work

In discussing accessible graphics it is useful to distinguish between two basic types of graphs: Object-oriented graphs, and

graphs of numerical data. Object-oriented graphs usually consist of discrete nodes with links between them. Examples include organizational charts, program flowcharts, and assembly instructions. Here the nodes represent components or processes in a system and the links represent relationships among these entities. In contrast, graphs of numerical data often do not have a well-defined, object-oriented structure. Rather, graphic elements such as points, lines, bars, and areas are defined and assigned in some organized way to the data values, and structure in the graph emerges from the relationships in the data. Making this latent structure comprehensible is typically the main purpose of the graph. Graphs of numerical data can take many forms including line and scatter plots, bar graphs, pie charts, and contour and surface plots. A widespread approach to creating accessible representations of these kinds of graphs is to map the data into a non-visual sensory channel, and to provide a means for exploring the data in that domain. Auditory (including synthetic speech), tactile, haptic, and multimodal graphs form the four main categories.

Auditory graphs

Next to vision, audition is arguably our most highly developed sense so many researchers have worked to develop data sonification tools to create accessible auditory graphs. Early work in this area includes the Accessible Graphing Calculator (AGC) [2] and the MATLAB-based SKDtoolkit [3]. Both tools were designed to produce auditory representations of simple x-y function graphs. The AGC mapped function magnitude onto tone pitch (log frequency) and “played” the graph as a musical sequence. SKDtools used a similar approach, but also provided spatialized rendering using stereo, and interactive “scrubbing”, to allow users to explore different regions of the graph.

In the intervening years, the field of data sonification has blossomed and now stands alongside computer graphics as an active research area [4]. Accessibility (to graphical data and information at large) continues to be a major focus in sonification research [5].

Tactile and haptic graphs

The tactile and haptic senses have also been used to create accessible graphics for the visually impaired. Traditionally, tactile graphs were created by hand using raised edges to represent lines and outlines, or layered materials to produce 3D contour maps. Vacu-formed plastics and electro-formed metals have also been used. More recently, digital tactile printing technologies have been developed that include heat-sensitive swell paper and embossing printers. Tactile graphs have been shown to be an effective means for creating accessible graphical representations [6].

Another line of research has taken advantage of recent developments in haptic technology to develop accessible graphs. Many of these projects have explored the usefulness of the PHANToM pantograph, a mechanical arm that can be outfitted with a variety of tools to allow point-wise probing of virtual

surfaces [7]. Other researchers have explored the utility of low cost force-feedback devices such as the Logitech WingMan [8]. Accessible haptic graphing technologies have great potential but the cost and evolving capabilities of the hardware, and the pointwise nature of interaction are significant limitations. If multi-touch haptics can be developed, it may provide capabilities that incorporate the best features of both the haptic and tactile modalities

Multimodal graphs

The widespread availability of multimedia computers has fostered the growth of multimodal approaches to accessible graphics. The promise is to leverage synergies between different sensory modalities (audition, touch, haptics, etc.) to create richer representations of graphical data. The NOMAD [9] was a pioneering multimodal graphics system that integrated tactile prints with a touch tablet that provided spoken audio feedback. Gardner and Bulatov [10] have produced a system that includes tactile, synthetic speech, and tone plotting tools. Wall and Brewster [11] have recently developed a system that combines a tablet, tactile mouse, and audio synthesis to create a two-handed multimodal graphics system.

Researchers have also integrated haptic interfaces with speech, auditory, and visual representations to create multimodal graphics tools. Grabowski et al. [12] combined a PHANToM with an audio synthesis system to provide audible collision and guidance cues to complement the haptic feedback. McGookin and Brewster [13] developed a system that allows haptic/auditory graphs to be developed interactively. Doush et al. [14] have recently developed a multimodal graphics system for representing Excel graphs and charts that includes a visual display and synthetic speech output in addition to haptics and audio.

Usability of accessible graphics tools

It is one thing to develop an accessible graphics system but another to develop a system that is usable and effective. Therefore system evaluation and testing is an important activity. Way and Barner [6] and have compared the effectiveness of tactile and visual representations and found that tactile graphs can be as effective as their visual counterparts. Members of the sonification community have done a wide range of studies that compare auditory and visual representations [4], finding that auditory representations can be effective for conveying relative magnitudes and differences but are generally not well suited for communicating absolute metric information.

Most usability studies have focused on simple x-y function graphs, and area charts, but evaluating accessible representations of multivariate data is also an important area for testing. Recently Jay et al. [15] developed and tested an audio/haptic system for exploring three dimensional data spaces and found 1) that multimodal rendering was superior to either audio or haptic presentation alone, but also that 2) there were also differences in the effectiveness of the audio and haptic modalities for identifying the elements in the space and determining their layout.

Experiments

The IVEO system allows the creation of auditory, tactile, and multimodal representations of multivariate 3D datasets, but relatively little is known about how usable such a system is, and what the contributions of each modality to the overall effectiveness of the system are. To address these questions we conducted an experiment where both visually-impaired and sighted but

blindfolded participants explored tactile and auditory graphs representing 3D surfaces. In separate studies we asked the participants to detect differences in the heights and widths of the surfaces and measured how effectively the tactile and auditory representations conveyed information about these surface properties. The following sections describe the stimuli and procedures used in the experiments and the characteristics of the participants.

Stimuli

To begin we had to create datasets representing 3D surfaces that we could use to study how effective the graphs are at conveying surface properties. Although 2D data arrays can represent 3D surfaces of arbitrary complexity, for several reasons we decided to start by studying Gaussian surfaces. First, Gaussians are spatially continuous and their parameters can be varied systematically to produce controlled changes in surface heights and widths. Second, Gaussians are used ubiquitously in science, mathematics, and engineering as models of data. Finally, using mathematics similar to Fourier analysis, arbitrary surfaces can be represented as linear combinations of simple Gaussians, so any insights developed by studying the non-visual representation and perception of 3D Gaussians are likely to generalize well to more complex surfaces.

Using the custom built application illustrated in Figure 1, we first defined two sets of 3D Gaussian surfaces. The “amplitude” set consisted of nine radially symmetric Gaussian surfaces of fixed width (proportional to variance = 0.2), that ranged in peak amplitude from 0.1 and 0.9 in 0.1 unit steps. The “width” set consisted of nine radially symmetric Gaussian surfaces of fixed amplitude (0.5), that ranged in width between 0.1 and 0.3 in 0.025 unit steps.

These 3D surfaces were then represented as standard 2D contour plots (orthogonal Z/height axis projection) with 12 quantization levels across the 0.0-1.0 amplitude range. Figure 2 shows the image sets produced by this process. Note that in the amplitude set, the number of contours in each plot is equal to the amplitude of the Gaussian. In the width set, each plot has five contours, but the spacing of the contours varies in proportion to the Gaussian’s width. In the amplitude set the plots ranged in physical size from 10 to 48 millimeters in diameter. In the width set the range was 21 to 54 millimeters. Each contour plot was stored as an object in the SVG file format. Separate tactile and auditory graphs were made from the contour plots.

The tactile graphs were printed on card stock with a ViewPlus Emprint embossing color printer driven by the IVEO software. Factory default embossing settings were used. The final tactile graphs consisted of blank sheets of cardstock with raised dots marking contour lines. Dot addressability was 1mm, but adjacent contours were a printed least one dot-space apart (2mm) for the smallest stimulus and ranged to 8mm for the largest. This spacing was chosen for practical reasons related to the design of the printer, but also assured that adjacent contours and/or contour shifts were at or above the typically cited 1-2mm threshold for tactile grating discrimination [16]. A representative tactile graph is shown on the tablet in Figure 3.

For the auditory graphs, the IVEO software was used in conjunction with the ViewPlus touch tablet to produce 2D “tone maps” analogous to the 1D tone plots produced by packages like the Accessible Graphing Calculator [2] and the SKDToolkit [3]. The software was configured so that consecutive levels in the contour plots were rendered as a series of MIDI-generated piano

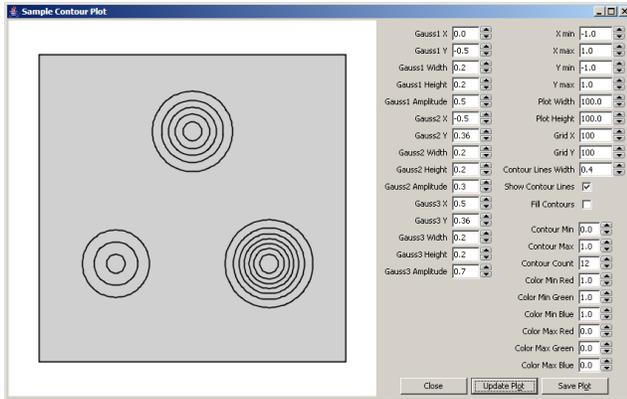


Figure 1. Gaussian contour plot generator application.

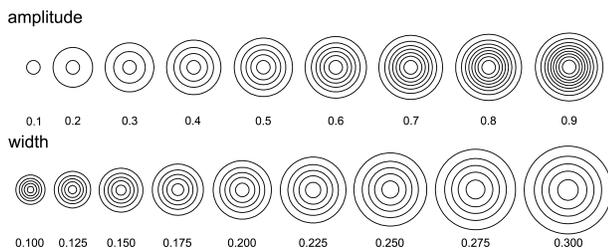


Figure 2. 3D Gaussian contour plots used in the experiment. Note that the images are shown at approximately 1/4 of their actual sizes.

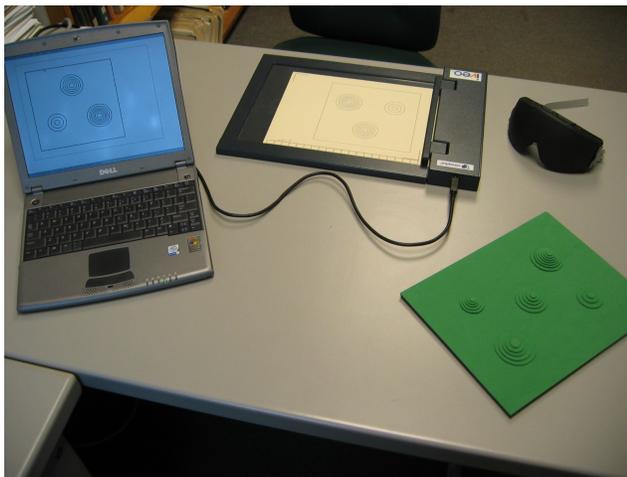


Figure 3. Experimental setup: On the left is a laptop computer running the IVEOSound software. In the center is the IVEO touch tablet with a representative tactile graph from the data set. Next to the tablet is the blindfold used by the sighted participants. On the right is the physical model used to familiarize participants with the graphical representations of the Gaussian surfaces.

tones starting at middle C on the keyboard. Crossing a contour caused the pitch to change to the next higher or lower keyboard note (semitone). Since 12 contour levels were used to represent the 0.0-1.0 amplitude range, the maximum change in pitch was one octave. The middle-C based twelve-tone scale was chosen as the representation space because it assured that the overall pitch range

would be of moderate frequency and that adjacent pitches would be easily discriminable.

Procedure

The experimental procedure consisted of two tasks in which participants were asked to detect differences in the properties the Gaussian surfaces represented by the tactile and auditory graphs. In the *amplitude task* participants judged differences in the represented heights of the Gaussian surfaces. In the *width task* participants judged differences in the represented spreads (standard deviations) of the Gaussians. The combination of tasks and graph types yielded four distinct experimental conditions amplitude/tactile (AT), amplitude/auditory (AA), width/tactile (WT), and width/auditory (WA).

In each condition, a participant was presented with a series of 8.5x11 inch “pages” generated by the software application shown in Figure 1. Each page consisted of three graphs arranged in an upright equilateral triangle 3.25 inches on a side. The graph at the apex of the triangle was designated as the “standard” graph, and each graph on the base was a “test” graph representing one trial in the experiment. This particular stimulus arrangement was chosen for testing efficiency given the constraints of the software but the psychophysical method is a standard yes/no paradigm [17].

Participants explored the graphs on each page with their fingers. In the tactile conditions participants dragged their fingers across each graph to feel the extent and density of the embossed contour lines. In the auditory conditions, participants dragged their fingers across the touch tablet, and contours were represented by changes in pitch. Participants were explicitly asked not to count contours when performing the tasks. Two steps were taken to make the tactile and auditory conditions directly comparable: 1) the tactile pages were always placed on the touch tablet (although the software was turned off), and participants were instructed to use a single finger to explore them; 2) to aid in orienting to the auditory pages, a tactile overlay was placed on the touch tablet that had a three rings of embossed dots to indicate the gross locations of the graphs within the tablet area (a single ring overlay was used and did not change with the individual stimuli).

There were 16 trials in each experimental condition. In the two amplitude conditions (AT and AA), on the first eight trials, the graph of the 0.5 amplitude Gaussian was used as the standard, and each of the other eight graphs (0.1-0.4 and 0.6-0.9) was tested against it. To determine if the absolute amplitude of the standard had an effect on performance, on the next four trials a 0.7 amplitude standard was compared against the 0.5, 0.6, 0.8, and 0.9 amplitude test graphs, and on the final four trials, a 0.3 standard was compared against the 0.1, 0.2, 0.4, and 0.5 tests. Analogously, in the two width conditions (WT, WA) on the first eight trials, the 0.200 width Gaussian was used as the standard for the other eight graphs in the set, and then the 0.250 and 0.150 Gaussians served as standards for the two wider and two narrower neighboring graphs in the set. On each trial participants were asked to judge whether the test Gaussian was taller/shorter than the standard (amplitude task) or wider/narrower than the standard (width task). Correct and incorrect judgments were recorded manually by the experimenter. In all conditions, the order of presentation of the test graphs and their left/right positions on the pages were randomized. The order of presentation of the different conditions (AT, AA, WT, WA) was balanced across participants.

Table 1. Characteristics of the visually impaired group

Participant	Age	Age at impairment	Visual function	Braille reader
11	25	7	No light sense	yes
12	20	birth	20/100, used blindfold	yes
13	45	25	Only light sense	some
14	50	birth	No light sense	yes
15	25	birth	No light sense	no
16	20	birth	20/200, used blindfold	no

Table 2. Experimental error rates

Amplitude task																	
standard		5					7					3					
test		1	2	3	4	6	7	8	9	5	6	8	9	1	2	4	5
parts. cond.		# of errors															
norm	AT	0	0	0	0	2	0	0	0	0	1	4	0	0	0	0	0
imp	AT	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
norm	AA	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
imp	AA	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0

Width task																	
standard		200						250				150					
test		100	125	150	175	225	275	300	200	225	275	300	100	125	175	200	
parts. cond.		# of errors															
norm	WT	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	0
imp	WT	0	0	0	1	0	0	1	1	0	1	3	0	0	0	0	0
norm	WA	0	2	2	5	4	2	2	1	2	3	4	2	0	1	2	1
imp	WA	0	1	3	5	5	2	0	0	2	3	3	1	1	1	2	1

Prior to testing participants were familiarized with the overall goals and procedures of the experiment. Before each of the four experimental conditions, participants were presented with a physical 3D model (shown on the right in Figure 3) fabricated from layered foam disks that represented the quantized Gaussian surfaces they would be exploring using the graphs. Then at the beginning of each condition, participants were given two familiarization trials where they explored the particular kinds of surfaces and graphs they were about to be tested on, and they were allowed to ask any questions they might have. On average, the experiment took about 45 minutes. Participants were compensated for their participation.

Participants

Six visually impaired and six normally-sighted adults participated in the experiment. All participants were university graduates or current university students, and all had at least high school level math experience. The two populations were mixed in gender and approximately matched by age, which ranged from 20 to 55. Table 1 summarizes the characteristics of the visually impaired participants.

The sighted participants all had self-reported normal or corrected-to-normal vision, but were blindfolded during the experiment to allow comparison with the visually impaired group. We were interested in comparing these groups because it is often the case that sighted but blindfolded individuals are used to test and evaluate assistive technologies for the visually impaired, but studies such as [18], have shown differences in sensory abilities between the blindfolded and visually impaired. For this reason we wanted to understand if there were significant performance differences between these groups with respect to using our technology.

In terms of tactile experience some of the members of the visually impaired group were Braille readers (with different degrees of self-reported competence). In terms of auditory experience, all participants had self-reported normal hearing, and some members of both groups played musical instruments, though none had professional-level training. None of the participants had prior experience with the IVEO hardware or software or with tactile or auditory graphs of the kinds used in the study.

Results

Table 2 summarizes the results of the experiment, showing the error rates for the amplitude and width tasks broken down by standard and test stimuli, participants (normal, impaired) and stimulus condition (AT, AA, WT, WA). Using these data we ran a series of ANOVAs (MATLAB “anovan”) to answer the following questions:

- Vision:** Do the visually impaired and sighted (but blindfolded) participants differ in their abilities to perform the tasks using the graphs?
- Modality:** For a given task does one type of graph allow more accurate discrimination of surface properties than the other?
- Range:** Do the magnitudes of the stimuli have an influence on how well participants are able to discriminate surface differences using the graphs?

Table 3. ANOVA statistics for the amplitude and width tasks

Amplitude task					
Source	SS	df	MS	F	Prob.>F
vision	0.014	1	0.014	0.030	0.874
modality	0.125	1	0.125	0.230	0.633
range	8.778	2	4.389	8.080	0.001
Errors	36.403	67	0.543		
Total	45.319	71			

Width task					
Source	SS	df	MS	F	Prob.>F
vision	0.500	1	0.500	0.430	0.515
modality	43.556	1	43.556	37.360	0.001
range	33.333	2	16.667	14.300	0.001
Errors	78.111	67	1.166		
Total	155.500	71			

Amplitude task: In the amplitude task participants were asked to discriminate between Gaussian surfaces of different amplitudes. Three standards (amplitudes 3, 5, and 7) were used for comparison. To investigate the effects of participant vision, graph modality, and stimulus range on performance we ran a three-way ANOVA on participant error rates. The statistics are summarized in Table 3 (top). The analysis showed no significant effects of either participant vision or graph modality, but a did show a significant effect of stimulus range ($F(2,67) = 8.08, p > 0.001$).

Multiple comparison tests (MATLAB “multcompare”) on the stimulus range effect showed that the mean error rate for the high amplitude standard (7) was significantly greater than for the low or moderate amplitude standards (3, 5). This result is illustrated in Figure 4 (top).

Interpreting the analysis, we can make several observations. First, overall error rates in this task were low, indicating good sensitivity for surface amplitude differences. Second, the low error rates coupled with the lack of measurable performance differences between the normal and impaired groups suggests that the graphs were effective for both groups, and that their usability was not significantly affected by the visual status of a user. Third, the lack of significant differences in error rates between the tactile and auditory graphs suggests that both modalities were effective as

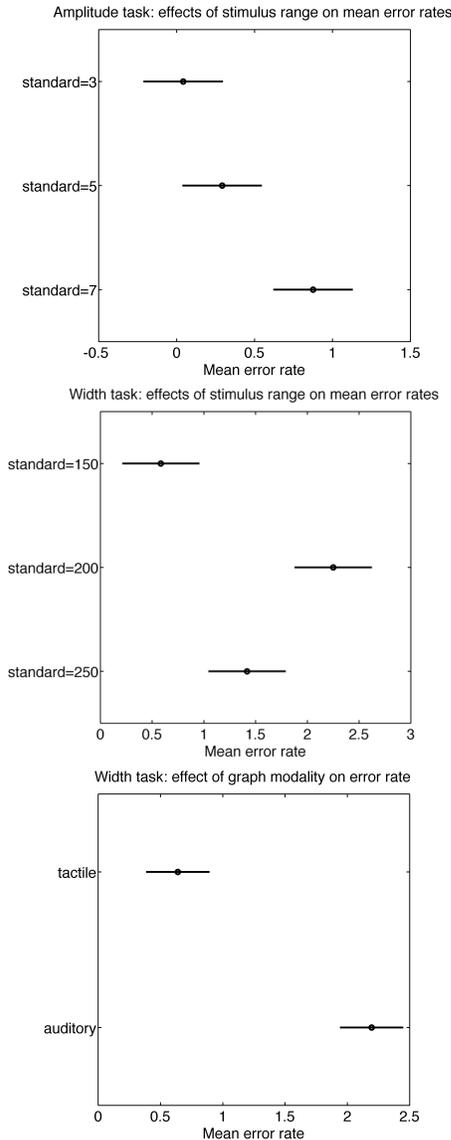


Figure 4. Mean error rate comparisons for the significant effects

non-visual representations of surface amplitudes. One caveat however is that there appears to be a relationship between surface amplitude and performance, with errors increasing significantly for comparisons between higher amplitude surfaces.

Width task: In the width task participants were asked to discriminate between Gaussian surfaces with different widths (standard deviations). Three standard widths (225, 250, 275) were used for comparison. Again, to investigate the effects of graph modality, stimulus range, and participant vision on performance we ran a three-way ANOVA on participant error rates. The results are summarized in Table 3 (bottom) and are somewhat different than those found in the amplitude task. Like before, this analysis also showed no significant effect of participant vision, and like before there was a significant effect of stimulus range, but in this case, there was also a significant effect of graph modality.

Multiple comparison tests on the stimulus range effect showed that the mean error rate for the narrower standard (150) was significantly lower than either the moderate or broad standards

(200, 250) that were not significantly different from each other. This result is illustrated in Figure 4 (middle). Testing on the modality effect showed that mean error rates using the auditory graphs were significantly higher than for the tactile graphs. This result is illustrated in Figure 4 (bottom).

We can make several observations about the data and analysis of this task. First, the average error rates were higher overall for this task than for the amplitude task, suggesting that participants found it more difficult to discriminate surface widths than amplitudes. The increase was not significant in the tactile case ($F(1,67) = 2.16, p = 0.147$), but was in the auditory case ($F(1,67) = 45.19, p > 0.001$). Second, as before, the error rates increased significantly with stimulus magnitude. Third, as before, there was no significant effect of participant vision. However fourth, but most importantly, participants showed significant and dramatically higher error rates in width discrimination using the auditory graphs. The increases were echoed by the participants' self-reports of the difficulty they had performing the task, and the frustration they expressed about the interface.

The key issue with the interface was that in the other three conditions, information about surface properties was *ordinally* related to the property (e.g. higher amplitude: more rings (AT); or higher pitch (AA), greater width: larger diameter rings (WT)) however in the auditory condition of the width task (WA), information about the surface was *metrically* related to the audio stream. Discriminating different surface widths required participants to move their fingers in a controlled way, and relate the distance moved to the changes in pitch (i.e. wider surfaces were signaled by larger distances between pitch changes). The participants found it difficult to control this interaction, which probably accounts for the significantly higher error rates in the WA condition. The take home message for designers is that they should be careful not to link critical information about the object being explored to precise, metric movements of the hands and fingers. Rather, the relationships between object properties and exploratory hand movements should be ordinal, with metric information delivered by some other modality such as synthetic speech or other non-visual means.

Conclusions and Future Work

In this paper we described an experiment designed to assess the effectiveness of the tactile and auditory graphing tools incorporated into an accessible graphics system. In four related experimental conditions visually impaired and sighted but blindfolded participants explored tactile and auditory graphs of 3D Gaussian surfaces and were asked to discriminate differences in surface amplitudes and widths. From the results of the experiment we can draw the following conclusions.

With respect to discriminating surface amplitudes, participants showed good sensitivity using either the auditory or tactile graphs. Statistical analysis showed low error rates and no significant differences in performance as a function of graph modality. This suggests that under the conditions tested, both types of graph are effective as non-visual representations of surface amplitude characteristics.

With respect to discriminating surface widths, participants again showed good sensitivity with the tactile graphs, but performance was significantly worse with the auditory graphs. Thus for discriminating surface widths, the tactile graphs were much more effective than the auditory ones, however as discussed above, this may be due to a user interface issue rather than a problem with auditory representations per se. The results suggest

that designers of auditory graphics systems should be careful not to link information access to precise metric movements of the hands or fingers.

In both tasks there is a relationship between discrimination accuracy and stimulus magnitude, with error rates increasing for higher and wider surfaces. These results suggest that there may be non-linearities in the tactile and auditory perception of surface properties. However, further work is necessary to reveal these functions.

Finally, both the visually impaired and sighted (blindfolded) participants performed similarly in all tasks, showing no significant differences in error rates in any of the experimental conditions. This suggests that the forms of auditory and tactile graphs tested are generally useful, and that their usability is not affected significantly by the visual status of a user. While this conclusion should be moderated by the understanding that this was a small study of a heterogeneous group, and that age, training, motivation, and other factors may affect performance, it does suggest that even users without significant experience with non-visual graphical interfaces can make good use of the system we have presented.

While these results are interesting and suggest that non-visual graph modalities may provide effective and accessible representations surface graphs for people with visual impairments, much more work remains to be done. First, within the current experimental framework, in the amplitude study, a greater range of surface amplitudes should be tested to determine the limits of amplitude discrimination using tactile and auditory graphs. Second, in the width study a new interface should be developed for the auditory graphs that does not tie graph information to precise physical interactions, and the width task should be retested. Finally, it would be interesting to generalize beyond simple symmetric 3D Gaussian surfaces and test how effectively the tactile and auditory graphs convey the features of complex surface data.

Looking beyond the current framework, accessible graphics tools for a much greater variety of numerical datasets (continuous and discrete functions of 1,2,..n variables), and a greater diversity of graphical representations (e.g. bar, line, area and scatter plots, color maps...) need to be developed and evaluated psychophysically. In addition it would be worthwhile to explore other the possibilities of using other aspects of sound such as timbre to represent graphical features. On the basis of this and future work it will hopefully be possible to develop effective non-visual graphics interfaces that will make the conceptual power of graphical representations universally accessible.

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