Feeling What You Hear: Tactile Feedback for Navigation of Audio Graphs

Steven Wall and Stephen Brewster
Glasgow Interactive Systems Group, Department of Computing Science
University of Glasgow, G12 8QQ, UK
e-mail: steven, stephen @dcs.gla.ac.uk
Tel.: +44 (0)141 330 4966

ABSTRACT
Access to digitally stored numerical data is currently very limited for sight impaired people. Graphs and visualizations are often used to analyze relationships between numerical data, but the current methods of accessing them are highly visually mediated. Representing data using audio feedback is a common method of making data more accessible, but methods of navigating and accessing the data are often serial in nature and laborious. Tactile or haptic displays could be used to provide additional feedback to support a point-and-click type interaction for the visually impaired. A requirements capture conducted with sight impaired computer users produced a review of current accessibility technologies, and guidelines were extracted for using tactile feedback to aid navigation. The results of a qualitative evaluation with a prototype interface are also presented. Providing an absolute position input device and tactile feedback allowed the users to explore the graph using tactile and proprioceptive cues in a manner analogous to point-and-click techniques.

Author Keywords
Tactile, audio, multimodal, graph, navigation, blind, accessibility, guidelines.

ACM Classification Keywords
H.5.2 User Interfaces: *Haptic I/O, User-centered design.*

INTRODUCTION
In this information driven age, the increased proliferation of digitally stored data and the growth in information made available online via increasingly sophisticated internet applications has frequently been denied to visually impaired and blind computer users due to the visual-centric nature of presentation methods employed. Understanding and manipulating data using simple visualizations such as graphs, tables, and charts is a very common task for sighted people, whether that is in interpreting stock market data, sporting statistics, tracking progress in a game, managing home finances, or numerous other vocational and recreational activities. The basic skills needed for interpreting and manipulating graphs are necessary for all parts of education and employment. The visually impaired community has highly limited access to data presented in these visual ways. It is currently very hard for them to create and manipulate simple visualizations, and collaborate with sighted peers using graphs and tables. Multimodal human computer interfaces such as haptic devices, text-to-speech applications and spatialised 3D audio can potentially offer a means for visually impaired and blind people to access numerical data in a dynamic manner, using the senses still available to them.

Audio representations are a common method of making data accessible to the sight impaired. Screen readers that can convert the desktop and common document formats (e.g. for word processing, spreadsheet or internet browser applications) are very commonly used within the visually impaired community. Access to data is achieved using the cursor keys and other keyboard shortcuts for navigation of the document. The disadvantage of this is that it is serial in nature, time consuming to navigate large data sets, places large demands on working memory, and hence makes it difficult to gain an overview of data series. Research in to sonification techniques has sought to overcome these limitations by representing data with musical sounds [1]. A parameter of the sound (for example, pitch) can be scaled to the value of the datum, hence data series can be browsed by making a rapid series of relative comparisons. By spatially panning the sounds it has been demonstrated that it is possible to browse two [2] or even three [3] data series in parallel.

Zhao et al.[4] proposed the Auditory Information Seeking Principle (AISP) to provide guidelines for sonification research, based on the visual information seeking principles of "overview, zoom and filter, details-on-demand" [5]. In the proposed model, querying data can be divided in to four stages: (i) "gist", a short auditory message describing an overview of the data series, (ii) "navigate", an iterative

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Figure 1a. VTPlayer mouse incorporating two tactile pin arrays.

Figure 1b. Close up of the tactile pin arrays, two four-by-four matrices of individually controllable pins (shown with fingertip for scale).

process of the user querying the data and receiving feedback, (iii) "filter", constraining the data set to a particular focus and (iv) "details on demand", selecting a datum or group of data to obtain specific details. Providing a pointing device and a structured, spatially distributed representation of a data series could help with navigation of audio based representations by overcoming the serial methods of presentation. However, point-and-click devices such as the mouse rely on visual feedback for planning and execution of target acquisition, making them inappropriate devices for the visually impaired.

The sense of touch is often employed in non computer based, or "static", accessibility aids to make text and images available to the visually impaired, using techniques such as embossed paper for Braille and tactile diagrams. Many sophisticated force feedback devices are available that could render compelling illusions of contact with virtual environments, including representations of data visualizations such as line graphs and bar charts, as first proposed by Fritz and Barner [6]. Wall and Brewster noted that visually impaired participants often possessed a strong capacity for memorizing and utilizing the spatial layout of a bar chart when browsing the data, which can be supported using haptic cues [7]. In this manner, the sense of touch can be employed as a feedback mechanism for planning and executing point-and-click style strategies for the visually impaired. In addition, audio information can be supplemented by providing indirect access to the data via haptic feedback for graph elements in a manner analogous to visual representations, for example, heights of bars, edges of pie slices or paths of line graph data series can all be represented haptically. Yu and Brewster note that spatial perception and proprioceptive cues are useful when comparing two similar bar heights on a graph [8].

However, force feedback devices are generally a cost prohibitive solution for most visually impaired individuals. Tactile display, that is, actuators which seek to display information via mechanical stimulation of the skin (for example, indentation or vibration cues) are becoming increasingly more prevalent. The technology required to create tactile displays is often much cheaper than that required for haptic force feedback. Vibrotactile transducers have gained wide acceptance through their use as discrete alerts in mobile telephones and pagers, and also within the entertainment sector as a means to provide increased feedback and immersion via handheld video game controllers. Further, tactile displays can be made smaller and are hence more portable and discrete for the individual to use. Vanderheiden proposed a "virtual tactile tablet", whereby the use of a touch sensitive tablet, in conjunction with a tactile display mounted on a pointing device (e.g. a puck or mouse) would allow the user to feel a tactile representation of a screen image at that point on the tablet. The tablet would allow the user to explore a document or computer desktop, perhaps supplemented by audio cues, while monitoring their position on the tablet [9].

Sensory substitution for the visually impaired using tactile displays can be classified as either a pictorial or an encoded rendering approach. The former involves the direct translation of an image to the tactile sense (for example, the raised outline of a letter, character or image) while the latter uses a more abstract representation, perhaps based on the affordances and constraints of the skin as a communicative medium (for example, the raised dot patterns of the Braille language). Some of the earliest work on pictorial rendering was the development of the Optacon (summarised in [10]), a commercially available device which converted printed text to a spatially distributed tactile representation on the fingertip. A miniature hand-held camera is used to detect light and dark areas of a page, and the resulting image is presented to the skin of the fingertip via a matrix of vibrating pins. Although reading speeds were significantly slower than Braille, the Optacon allowed blind people to access any text or graphics without having to wait for it to be first converted into Braille.

The VTPlayer mouse (www.virtouch.com) is a commercially available, mouse based device that incorporates two tactile arrays, each consisting of a 4 by 4 array of individually controllable pins (Figures 1a and 1b). The pins can be raised or lowered by controlling software. During standard operation, the state of the pins is controlled by the pixels directly surrounding the mouse pointer. Using a simple threshold, a dark pixel corresponds to a raised pin, and a light pixel corresponds to a lowered pin. The user rests their index and middle fingers on the arrays during normal operation and can feel a tactile representation of images presented on the screen. In this fashion, a blind user could potentially interpret the tactile cues and use them to navigate about a desktop environment, document or user interface. The VTPlayer offers a dynamic means of interacting with tactile representations of data, without the need to manufacture unique tactile diagrams for each data set.

A device such as the VTPlayer potentially can be used to improve navigation and browsing of audio representations of data series, by allowing sight impaired computer users to interact with data in a point-and-click style. The results presented in this study focused on the use of bar charts for representing data series, as they are one of the most simple and rigidly structured types of graph. All the bars must start at the X axis and extend vertically upwards in the Y dimension. As visually impaired people may not have experience of visual representations of data series it was important to choose a representation that could be easily verbally explained to them within the time scale of the evaluation.

A requirements capture study was conducted with a group of blind and visually impaired individuals in UK further education. The purpose of this was to find out about their habits and requirements during computer use, in particular when working with numerical or tabulated data. Participants were interviewed to learn more about the positive and negative aspects of commonly used accessibility aids, in this context. A short think-aloud study was conducted with a raised paper tactile graph in order to gain some insight in to how tactile feedback aids navigation and acquisition of data in a non-computer mediated environment. This led to the design of a prototype system. An initial evaluation based on qualitative data from a think-aloud experiment was also conducted. Sonification techniques are relatively well understood, therefore this study focused on the novel aspect of providing tactile feedback to aid navigation. For this purpose, limited audio feedback was provided in order to encourage the participants to focus on the tactile cues.

REQUIREMENTS CAPTURE

In order to prompt initial designs, a series of interviews were conducted with blind and visually impaired participants at the Royal National College for the Blind (RNCB), Hereford, England, in March 2005. The interviews focused on general use of computers, and more specifically on access to simple visualizations (such as bar charts and line graphs) through tactile and audio accessibility aids. Initial reaction to the VTPlayer was also solicited from the participants.

Four participants took part in the interviews, three were students at the RNCB, and the other participant was a visually impaired member of staff at the college, who had recently attended as a student. All subjects were blind or visually impaired from an early age, and all had studied, or were studying, to a level of “further education” in the UK (e.g. A-levels, B-TEC, NVQ). All were familiar with Braille.

Procedure

All the interviews followed the same basic structure. The purpose of the interview was explained to the participant, and they were then asked to supply details such as their age, level of residual sight, and about the subject they were studying at the college.

The interview began quite generally with a discussion about general use of computers. This included for what purposes the participant used computers at home and at work, and giving details of any accessibility aids that they used. The interviewer also asked the participant if they used other non-computer based accessibility aids such as tactile raised paper diagrams and Braille, and their most common uses.

The participants were then more specifically asked about how they would work with numerical data, for example, when managing their home finances or working with some tabular data in mathematics or a science. They were asked to detail specific methods of accessing this data, and the positive and negative aspects of any accessibility aids that were employed for this purpose. The participant was asked to further elucidate on any common actions that were made particularly difficult by lack of access, or particular actions that were not supported by a specific method of access.

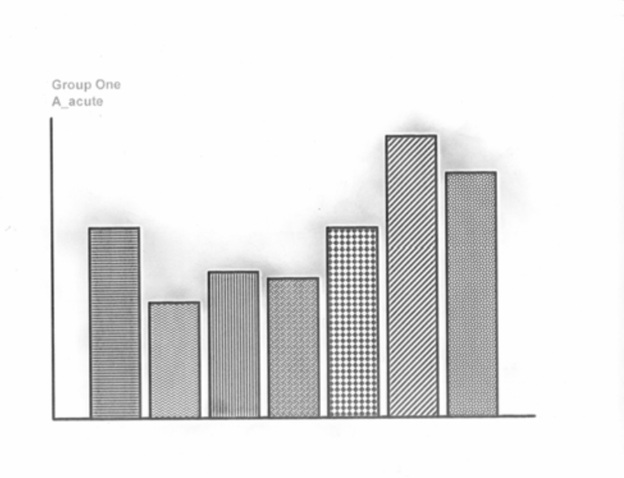

Figure 2. Tactile raised paper representation of a simple bar chart, as used in the think-aloud study.

The following part of the interview was a short think-aloud exercise to gain some insight in to common strategies used to explore tactile raised paper diagrams. The participant was presented with a tactile raised paper bar chart, consisting of axes and seven bars. No labels, titles or legends were provided so as not to distract the participants from focusing on the tactile representation of the bars (Figure 2). Several hypothetical questions were posed sequentially to the participant, who was asked to demonstrate how they would extract the necessary information from the tactile representation of the bar chart. The questions were chosen to observe strategies when working with, between and beyond the data [11]. During the task, the participants were encouraged to think-aloud and describe the strategies that they were employing. The questions were (a) how would you find the value of a particular bar (working *with* the data), (b) how would you make a comparison between a subset of the bars and find the highest (working *between* the data), and (c) if the height of a particular bar was doubled, how would you compare the new value with the current value of a second bar (working *beyond* the data)?

For the final part of the interview, the participant was introduced to the VTPlayer mouse, in order to gauge their initial reaction to the device. The interviewer explained how to use the mouse, how the tactile display worked, and the basic principles of exploring with the device. A black and white bar chart was created and displayed on screen using the Microsoft Excel spreadsheet package. Hence, by moving the mouse, the participant would be able to feel features of the graph. This representation was chosen so as to be directly analogous to the raised paper representation previously employed in the interview. For this reason, no audio feedback was provided so that the participant would focus their comments on the tactile representation. No questions were posed on the data; instead the interviewer would provide a walk through of the features on the bar chart for the participant, describing what they were feeling with the tactile displays. The participant was again encouraged to think aloud as they explored the graph with the mouse.

Afterwards, the participant was asked for their opinion on the mouse, whether it was something they could imagine themselves using in the future, how they would summarize the device in a couple of sentences to a colleague, and to provide three good points and three bad points about the device.

Finally, the participant was asked to provide feedback on the interview procedure and the conduct of the interviewer, before being thanked for their participation and reimbursed for their time. The entire procedure took between 60 and 90 minutes, dependant on the participant.

General Use of Computers

All participants reported using computers extensively, both for educational or vocational purposes (where appropriate) and also in their spare time. The most commonly reported uses were for e-mail, word processing, browsing the internet, and chat software such as MSN Messenger. None of the participants used a mouse, which was impossible for them due to lack of the visual feedback channel.

Accessibility aids were essential for the participants to use a computer. The screen reading software "Jaws" (www.freedomscientific.com) was unanimously the most popular aid (other screen readers, such as "Supernova" (www.dolphinuk.co.uk) were not as popular). The user navigates the desktop using shortcut keys (cursor keys are very common for navigation) and listens to synthesized speech of icon labels and text in applications. In this fashion, a visually impaired user can "browse" the desktop and launch applications, create and review documents with a word processor, send and receive e-mails, and use real time text chat software, such as MSN messenger. Some specialist software that participants used for their courses was not compatible with Jaws. Participants also reported difficulty in obtaining an "overview" of a screen layout through speech output, and the memory demands incurred through use of many shortcut keys for navigation.

The other commonly mentioned accessibility aid was a Braille display. This is a device which is placed in front of the keyboard, and can present a line of text to the user in the Braille alphabet, using an array of refreshable displays. Common reported strategies for use included using one hand to navigate through the document using the cursor keys, while the other hand read from the display. The Braille display was sometimes used alone, but sometimes in conjunction with the Jaws screen reader.

Static Display Methods

The non computer based methods of representing data that were most commonly used by the participants were raised paper diagrams and Braille transcriptions. Raised paper diagrams were used extensively in education, but minimally employed once leaving school. Braille was used more commonly for personal leisure activities, for example, reading a book.

Raised paper diagrams

It is often the case that tactile printed media cannot suffice to provide the "complete picture" alone, and a sighted person's verbal description of a tactile graph or image is also required to guide the visually impaired user's exploration strategies. This is mainly due to the spatial constraints of the media, which enforces a limit on the amount of information that can be reasonably displayed on, for example, a single piece of paper.

When working with the tactile representation of a bar chart, the first action that all the participants took, even before questions were posed, was to feel over the graph with both hands to obtain a rapid overview of the information available on the page. This included gaining a rough idea of how many bars were in the chart, where particularly high bars were located, and any particularly low bars. Also the participants checked for resources, such as legends, axes and labels. The axes were of particular importance in helping the participant ground their subsequent exploration of the graph.

When working with the data to find values for bars, a common strategy was to trace the y-axis with the left hand, and the relevant bar with the right hand. The right hand was then brought across to meet the left hand at the y-axis and the data could be read off from Braille values or by counting gridlines. Relative comparisons between bars were very quick, particularly when two bars were adjacent in the graph. This could be accomplished by the participants very quickly and efficiently by using both hands to feel for the tops of the relevant bars and make a judgment as to their relative heights.

Working beyond the data proved to be particularly troublesome for all the participants (a typical question for working beyond data would be "if bar 2 is doubled in height, how much higher is it than bar 1?"). Participants remarked that the question would be less daunting if quick and easy access to exact numerical values were provided, but this was not normally the case with raised paper diagrams. Most participants who attempted the question (some did not) resorted to trying to trace above the second bar to twice the height. Without constraints and guidance this proved extremely difficult for them.

One participant remarked that salient features on graphs, such as data lines or axes, were often "highlighted" in a tactile manner by adding strips of adhesive material to the feature to raise their height. This echoes the findings of Challis and Edwards [12], who identified the height of a tactile relief as an important filtering mechanism.

Braille Tables

On the whole, Braille was more extensively used for personal activities, such as reading during leisure time. Participants remarked that tabular information, for example train times, would often be presented in a Braille format. As with standard Braille text reading, this is a two handed operation, with the right hand reading and the left hand providing guidance. The main problem with Braille representations is that dense tables can easily become cluttered with information due to the space required for the Braille characters. This had the knock-on effect that tables transcribed in Braille often could not preserve their original layout due to space limitations. This makes communication between a sighted person and visually impaired person using the same tabular data very difficult, as constancy of layout cannot be guaranteed between the two representations.

Dynamic Display Methods

Dynamic representations of data usually involve a technical device that mediates the information, or a microprocessor which controls the flow of information to the user. Examples of this include screen reader software and tactile displays. It is important to note that this section is not an exhaustive discussion of all accessibility technologies available to visually impaired people, and instead focuses on those technologies that commonly arose during the interviews.

Screen Readers

Screen readers are extensively used by blind individuals for access to text. With tabular data, the use of short-cut keys was increased, due to the need to tab and cursor between cells in the table. This in turn led to two common issues for participants. Firstly, memory demands were increased, due to the need to remember information pertaining to column and row headings while exploring the table. A "place marking" feature in Jaws allowed the users to place external memory markers that can be used to alleviate the problem somewhat, although this does increase the number of shortcut keys that need to be remembered. Secondly, non-intuitively placed tabs and cells make it difficult for a visually impaired person to get an accurate mental image of a table. Again, this can cause problems when collaborating with sighted people working with the same data, as verbal references to relative positions on the table (e.g. "somewhere in the bottom right of the table"), become largely meaningless to the blind person. Indeed, navigation and problems with the structure of a table can become so distracting that a blind person will often convert the table to a paragraph for browsing, thus completely changing the presentation of the data.

The Talking Tactile Tablet (T3)

The T3 [13] was developed in conjunction with the RNCB, Hereford, and as such, all participants were very familiar with the device. The device incorporates a pressure sensitive tablet, on to which is placed a tactile overlay, produced in exactly the same manner as a standard tactile diagram. Speech output can then be associated with regions of the diagram, such that the user can press the diagram and receive spoken information relevant to the tactile image. This information can be "nested" so that subsequent presses take the user deeper in to a menu of information. The T3 has been extensively applied for various topics, including a world encyclopedia with information linked to countries on a tactile map of the globe. The design of the T3 allows the use of traditional tactile diagrams with dynamically created audio information. This overcomes the traditional drawbacks inherent in the static nature of tactile diagrams, and allows information to be presented in speech that would otherwise clutter the diagram with Braille. The system is accessible enough that blind people can use the device to create their own content. Pioneering research on the development of combined audio feedback with static tactile diagrams was performed by Parkes [14].

Without exception, all of the participants in the interviews praised the T3's approach to making diagrams accessible. They felt that a "good overview" of the data was available through the multimodal combination of touch and speech. Given development of appropriate content, it was felt that the T3 could provide access to graphs and numerical data.

VTPlayer Tactile Mouse

Using the VTPlayer was a new experience for all the participants and they seemed positive regarding the potential benefits of the dynamic tactile display. The negative side of the novelty was that the participants remarked that the sensations provided by the device were “strange” or “weird”. This may have been related to the fact that the closest relative of the VTPlayer technology encountered by participants would be dynamic Braille displays. These devices are refreshed at a relatively low frequency and the user controls them via discrete cursor key strokes, rather than navigating a spatial continuum, as with the mouse. Further, this similarity with Braille technology led to further confusion, as it seemed that several of the participants were attempting to attribute meaning to the status of the individual pins, rather than seeing the pins as a whole, or as part of an image. Several participants attempted to use the mouse with two hands and the index fingers of both hands on the displays (as would be the case for reading/navigating Braille), rather than the index and middle finger of one hand used in standard mouse operation. The lack of familiarity with a mouse may have contributed to this confusion.

Participants remarked negatively on the small display area (effectively two fingertips in size) and the low resolution of the device, which made it extremely difficult for the participants to build up an overview of the image they were viewing.

The use of textures on the bars was particularly confusing for the participants. As the VTPlayer pins have only two height levels (raised or lowered), it was difficult for users to disambiguate the textures from other resources in the graph, such as the axes or the edges of the bars. The patterns of the textures also made the pins change very rapidly during movement, which the participants found quite disconcerting.

A lack of constraints and guidance proved to be a significant problem for all the users. During exploration of the bar chart it was a common occurrence for users to stray off the bar chart and on to menus that surrounded the bar chart on the GUI. Participants identified a key or legend as crucial to helping them understand the different parts of the graph. In particular, the axes need to be delineated in some way that makes them easy to find and follow.

Despite finding the mouse difficult to use, the participants thought that with more training time they could possibly get used to it. However, they expressed a wish to able to use the device without guidance from a sighted colleague or teacher working alongside them. The mouse should be able to be used independently by visually impaired people.

Summary

The following guidelines for designing a tactile feedback interface to support navigation were extracted from the requirements capture:

1. The system should allow the user to quickly orient themselves within the workspace. Resources that can be used to ground further exploration, such as axes and legends should be easily obtainable and unambiguous. The height of the tactile relief is important as a filtering mechanism to allow resources to be located quickly and easily.
2. The use of a mouse to explore the graph was not recommended, as the vast majority of visually impaired people have no experience with a mouse at all. The tactile feedback was too limited in size and resolution to provide sufficient contextual information to allow the user to explore the graph. An alternative means of input therefore had to be used. A common strategy with other accessibility aids was to use one hand to interpret the information, while the other hand guided or controlled exploration. This could be observed with non-technical aids such as Braille or raised paper diagrams, or with dynamic displays such as the use of cursor keys for controlling a refreshable Braille display.
3. The use of shortcut keys should be avoided. Many users will already be employing a screen reader that relies extensively on the keyboard for navigation.
4. Audio should be used where appropriate, in order to provide information in a manner that does not clutter the tactile representation, for example, speech or non-speech audio could be used to replace texture cues to allow discrimination between different bars. Synthetic speech is good for providing precise information regarding the data, and most visually impaired people are very efficient at interpreting it due to the extensive use of screen readers.
5. The representation employed should seek to preserve the layout used by sighted users in order to allow communication and collaboration between sighted and visually impaired people working with the same data.

These guidelines were used as a basis to design a prototype system to support navigation of data series for blind computer users, incorporating the VTPlayer mouse.

FIRST PROTOTYPE DESIGN

The prototype system used a stylus and Wacom Intuos 2 graphics tablet (www.wacom.com) as an input device. The user controlled the mouse pointer using the tablet with their dominant hand. The non-dominant hand rested passively, with the index and middle finger on the VTPlayer’s tactile displays. The mouse input was disabled, thus exploration was controlled using the tablet, while a tactile representation of the area of the screen underneath the pointer was perceived on the non-dominant hand (Figure 3).

The key design points of the prototype system were as follows:

1. The graphics tablet worked as an absolute positioning device, thus providing a spatial frame of reference for grounding exploration and communication (e.g. "It's on the far right of the graph"). As the mouse is a relative position input device it does not provide these benefits, and exploration strategies must be planned purely from the tactile feedback, which was too limited in size and resolution for this purpose. The size of the graphics tablet is approximately landscape A4, therefore comfortable for the user to reach without stretching [12].
2. The tablet was augmented with tangible X and Y axes, providing a reference which the user could quickly locate to guide and constrain their subsequent exploration of the graph. Representing the axes with a tangible tactile relief would allow them to be quickly disambiguated from the bars on the graph and employed as a position reference that is easy to locate, identify, and subsequently return to (as recommended by Sjostrom [15]).
3. The dynamic information to be represented, that is, the data on the bar chart, was rendered using the VTPlayer device. This offers tactile feedback for navigation ("Am I on a bar?") and indirect access to data values ("How high is the bar?") without recourse to a dedicated tactile paper representation that would be slow and problematic for a sight impaired person to produce without assistance.
4. Buttons on the stylus could be used to trigger speech audio feedback providing information about the bars (titles and values). This would prevent the tactile representation from becoming too cluttered with information, and provide "details on demand" which could be used to resolve comparisons between and beyond the data represented on the graph.

In order to rapidly evaluate the design, a prototype was created by scanning raised paper graphs to create a digital image file. By displaying this on screen with a standard image viewing program (Windows picture and fax viewer) the graphics tablet could be used to move the mouse pointer and subsequently perceive a tactile representation of the graph on the VTPlayer at no development cost. The graphs consisted of seven bars and the X and Y axes. The bars were represented by black edges on a white background (Figure 4). No fill or textures were employed on the bars. A representation directly analogous to visual bar charts was chosen in order to promote communication between visually impaired users and sighted users.

Figure 3. A user interacting with the prototype interface. Input is controlled via the graphics tablet with the dominant hand, while the non-dominant hand receives tactile feedback.

Audio feedback was limited due to the lack of a dedicated application for the prototype system, therefore querying the software for information on the bars was simulated by the experimenter role-playing the speech feedback. The participant could verbally prompt the experimenter to speak the name of the current bar and its value, analogous to a button click on the stylus. This allowed the subsequent evaluation to focus on the appropriateness of the tactile feedback and the graphics tablet for navigation purposes. The participants did not have to attend to any sonification of the data, hence the evaluation could be focused on the novel aspect of the interface. Should the prototype receive a positive response, an application can be created incorporating full audio feedback, and subsequently evaluated.

EVALUATION OF THE PROTOTYPE

To rapidly evaluate the initial design for the prototype tactile visualization system, a second series of interviews with blind and sight impaired users were conducted at the RNCB, Hereford, England, in July 2005. The interviews consisted of a walk through and demonstration of the new interface and a series of user tasks to prompt opinions on the interface. Participant comments would be used to gauge user reaction, and to inform a second iteration of the design prior to developing a software application.

Five participants took part in the evaluation, four were students at the RNCB, and the other participant was a visually impaired member of staff at the college, who had recently attended as a student. All subjects were blind or visually impaired from an early age, and all had studied, or were studying, to a level of "further education" in the UK (e.g. A-levels, B-TEC, and NVQ). All were familiar with Braille. 3 of the 5 participants took part in the requirements capture previously described.

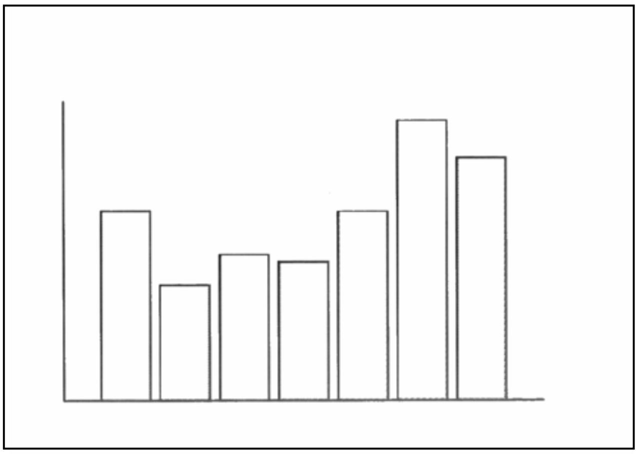

Figure 4. Example of a scanned representation of a tactile bar chart used in the prototype study.

Procedure

Participants were introduced to the prototype by a series of tasks that gradually increased in complexity. Initially, the participant was handed a tactile raised paper representation of a black and white checkerboard pattern. After exploring this, they were presented with an identical pattern via the prototype interface. This was used to introduce the concept of the relationship between stylus movement and the output on the tactile display. Using the graphics tablet as an input device was introduced using an analogy to the T3 device, with which all participants were familiar.

Once familiar with the device, the participant was handed a tactile raised paper bar chart and given time to familiarize themselves with its content in the standard fashion using both their hands. The participant was informed that the bar chart had seven bars and that each bar represented the average national income per person in the UK, for each year between 1992 and 1998. Once they had familiarized themselves with the bar chart they were presented with the same chart on the tablet and tactile display system. The experimenter offered verbal prompts to aid the participant in using the resources of the interface, such as using the tangible axes to orient themselves. When the user was comfortable with the interface, they were asked by the experimenter to describe the overall trend of the data on the graph (e.g. was the national average income increasing or decreasing over time), and locate the highest bar and query the interface for the value.

The procedure was repeated again with three more bar charts (time permitting), but without the tactile raised paper representation being shown prior to the tactile display version. Instead, the participant could view the raised paper version after completing the questions, in order to verify their impression of the data. All the bar charts contained seven bars and represented (i) the average rainfall for several different cities in January, (ii) the rainfall for the same seven cities in September, and (iii) the results of a traffic census (number of vehicles using a particular road) for the seven days of the week, respectively.

During all stages, participants sat with an experimenter and were encouraged to think-aloud and discuss what procedures they were following to extract information, any problems they were having, what they thought was particularly good or bad about the interface, and any other interesting points.

After the experiment, a post-hoc interview was conducted. The participant was asked if they could imagine using this system in the future, how they would quickly summarize the system to a colleague, and for three good points and three bad points about the interface. The participant was then thanked for their contribution and reimbursed for their time. The entire procedure was limited to 60 minutes per participant.

Results

The reaction to the prototype system was very positive. Users found the concept of using the graphics tablet with the dominant hand to explore the tactile graph with the non-dominant hand very easy. They were able to answer the questions posed by the experimenter, and many were able to provide a verbal description of the data represented by the graph when prompted. Participants were satisfied that the virtual representations were equivalent to the tactile raised paper graphs that were shown as part of the evaluation. Users who had previously evaluated the mouse based control several months prior expressed a much greater sense of “being in control” while using the graphics tablet.

More verbal guidance was required from the experimenter than simply naming the bars and their values. The participants would occasionally query the experimenter regarding their position on the graph when they were outside bars.

Participants were able to work using the edge based representations, but several commented that solid filled bars would be better, as this would provide an immediate indication as to whether the user was on a bar or not when they placed the pen on the tablet. This was not always possible with the edge based representations if the pen was placed within a bar such that no edges were shown on the tactile displays.

SECOND ITERATION OF DESIGN

During implementation of the interface as a software application, several improvements were made based on the evaluation of the prototype, as follows:

- Bars were rendered as filled rectangles rather than just edge based representations, thus, it is quick and easy for a user to ascertain if they are on a bar or not [12].
- Based on the information the participants queried the experimenter about, the speech feedback would be

improved to provide contextual feedback on the user's location in the graph when they clicked the stylus button. Thus, the information spoken will be either (i) the name and value of the bar the user is on, (ii) between two bars, in which case speak both bar names, (iii) directly above a bar, in which case provide an indication of this and the name of the bar, or (iv) outside the bounds of the graph, in which case indicate the direction.

The full application will be evaluated with visually impaired users and compared to current "best-practice" techniques for access to numerical data, for example, sonification applications, the T3 or screen reading software.

CONCLUSION AND FUTURE WORK

This paper has outlined the requirements capture, extracted guidelines and presented a preliminary design for an interface that uses a tactile display to aid sight impaired individuals' navigation of simple data visualizations. Computers are now an integral part of many visually impaired and blind individuals' lives, and they are extensively used for preparing reports for work, browsing the internet, and keeping in touch via e-mail and web-chat applications. However, spreadsheets and other applications that rely on tabular, numerical, or graphical data still present an obstacle to most visually impaired users. Raised paper tactile representations are not utilized much outside the classroom (most likely due to the need for sighted assistance during production, the need for bulky, expensive, specialist equipment and problems of storing and relocating hard copies), and screen reading software access is laborious and sequential, necessitating high memory demands, both for the data and for short cut keys. The interface described in this paper augments an audio (speech) based representation of a bar graph by improving navigation of the data with an absolute pointing device (a graphics tablet) and a tactile display.

The limited size and resolution of the tactile display area made it difficult to use this information to plan and perform movements in a manner analogous to the role of visual information when a sighted person uses a standard mouse. The graphics tablet alleviated this problem to a degree by allowing the users to employ the consistent reference frame of the tablet to direct their exploration; this was further augmented by providing a tangible relief of the X and Y axes of the bar chart. The tactile arrays of the VTPlayer provided feedback on the position and dimensions of the bars for navigation and data access, in a manner analogous to visual representations of bar charts. The dynamic nature of the VTPlayer means it can be quickly and easily reconfigured for different data sets, without the need to manufacture a new tactile relief for each data series. The results of the prototype evaluation show that it is possible for visually impaired users to use the tactile cues and graphics tablet to explore a representation of a bar chart. The evaluation procedure focused on the novel aspects of the interface, that is, the use of the tactile feedback and the graphics tablet. A dedicated application will be developed that incorporates non-speech audio feedback (sonification) of the data, in order to evaluate the efficacy of a truly multimodal representation (tactile and audio feedback).

With reference to Zhao's ASIP [4], incorporating a point-and-click style of interaction with an absolute position device and tactile feedback has enhanced step (ii), "Navigate" of the principle. A point and click metaphor overcomes the limitations of serial access to spoken or sonified data series. In future work, performance of the tactile display and tablet interface will be compared to current "best-practice" interfaces for navigating audio representations of data series (screen reader, T3, sonification techniques) to formally verify any increase in speed and accuracy. The interface also supported step (iv), "Details-on-demand", by allowing the user to request a synthesized speech output of the name of the bar and data value. In the next stage of development, it is planned to add sonification off the data series in order to support (i) "gist". It is also possible that the point-and-click method of interaction and tactile feedback could help in supporting (iii) "filter", by allowing the user to click and select a subset of the data series they are interested in.

Moreover, introducing a spatial frame of reference for the audio representation analogous to a visual graph can potentially support collaboration and communication between visually impaired people and sighted colleagues working with a shared representation. Working with the absolute pointing device promotes the use of terms of reference relative to this framework (for example, "on the left hand side of the graph") through the proprioceptive feedback available when using the graphics tablet. This will also be investigated in future work.

Bar charts were chosen for this application as they are the most structured representation of numerical data. However, they are not always the most appropriate depending on the nature and amount of data to be represented, and the information the user wishes to extract from the relationships within the data. In future it would also be beneficial to investigate how the interface performs for less structured forms of graphs with more sparsely distributed data such as scatter plots and line graphs.

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