Tac-tiles: Multimodal Pie Charts for Visually Impaired Users

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ABSTRACT

Tac-tiles is an accessible interface that allows visually impaired users to browse graphical information using tactile and audio feedback. The system uses a graphics tablet which is augmented with a tangible overlay tile to guide user exploration. Dynamic feedback is provided by a tactile pin-array at the fingertips, and through speech/non-speech audio cues. In designing the system, we seek to preserve the affordances and metaphors of traditional, low-tech teaching media for the blind, and combine this with the benefits of a digital representation. Traditional tangible media allow rapid, non-sequential access to data, promote easy and unambiguous access to resources such as axes and gridlines, allow the use of external memory, and preserve visual conventions, thus promoting collaboration with sighted colleagues. A prototype system was evaluated with visually impaired users, and recommendations for multimodal design were derived.

Author Keywords: Tactile, tangible, graphs, blind, accessibility.

ACM Classification Keywords: H5.2 User Interfaces: *Haptic I/O, User-centered design.*

INTRODUCTION

With today's proliferation of digitally stored data, and its widespread availability via the internet, a common problem facing blind and visually impaired computer users is how to obtain access to this growing resource. Browsing of text based documents is well facilitated by popular screen reading software (for example, Jaws by Freedom Scientific), which converts text to a stream of synthetic speech. However, graphical elements such as pictures, charts and tables are less well catered for. An alternative textual description can be provided, but in many cases this is not equivalent to the rich, distributed cues that are available for a sighted person looking at an image.

In particular, lack of access to data visualisations, such as line graphs and bar charts provides a hindrance to a visually impaired person who wishes to study a numerate discipline such as maths, economics or the sciences. These sectors are also denied access to this pool of potential talent, due to lack of access to teaching media. Blind students are often taught how to use spreadsheet software, such as Microsoft Excel, however, a sighted person's assistance is often required when it comes to verifying any visualisations that the student must create, which can be disheartening for a visually impaired learner seeking to foster independence.

Figure 1: Prototype Tac-tiles system. Graphics tablet augmented with a tangible pie chart relief, with dynamic tactile display for non-dominant hand.

Traditionally, several low-tech methods are used in schools and colleges to make accessible versions of common visualisations. For example, pins can be stuck in a cork board to represent data points, and joined by rubber bands in order to represent graphs and charts. Special heat-raised paper can also be employed to generate a tangible representation of monochrome graphics, by printing a suitably formatted representation, and passing it through a special heater.

Care needs to be taken to format these tangible representations, as they can become cluttered with information, and cues that are visually discriminable may not always be discriminated so easily by touch. For these reasons, the assistance of a sighted person with specialist knowledge of how to format and generate the representations is often required. Low-tech tangible representations of data are inherently non-dynamic and slow to produce. They are also difficult to store and subject to wear-and-tear; a student's work will often have to be destroyed at the conclusion of a class, so the materials can be reused by another student, which can also be very discouraging for a student wishing to achieve in a numerate discipline.

Figure 2: Using the Optacon device to read text. A hand-held camera detects light and dark areas of the page and converts to a vibrotactile pictorial representation, presented to a finger on a vibrating array.

However, low-tech representations do present a number of advantages.. One means of preserving these advantages in a digital tool may be to use virtual reality technologies such as haptic interfaces or tactile displays that allow for development of dynamic representations of data that are accessible to visually impaired people using the sense of touch. In this paper we outline the design and an initial evaluation of the "Tac-tiles" system (Figure 1), an accessible interface based on tactile and audio representations of common visualisations such as bar charts, pie charts and line graphs. The system uses a graphics tablet augmented with tangible overlays and a dynamic tactile pin-array. Previously, we have investigated representations of bar charts [11]. In this paper, we focus on the design of a multimodal representation of pie charts. Pie charts can be especially problematic for visually impaired users, as estimating angles is perceived as being difficult through touch, and creating circles is problematic using current pin and cork-board techniques. Firstly, we consider previous work in the area of accessible digital media for visually impaired users. In particular the review focuses on the use of dynamic multimodal (haptic and audio) feedback. We then present guidelines derived from an initial requirements capture aimed at identifying the benefits of low-tech tangible media. These guidelines were used to derive initial designs for the system. Finally, the results of an initial, qualitative usablitity evaluation with visually impaired users are presented.

PREVIOUS WORK

Several previous research endeavours have attempted to use digital technology to increase access to graphical teaching materials and visualisations. The earliest example of this was the Optacon (Figure 2), an electromechanical device which used a miniature handheld camera to capture information from printed media [1]. This was converted to a vibrating matrix of pins, which could be used to display letters and shapes. Comprehending text with the Optacon was slower than with Braille, but it allowed a blind person access to printed documents that had not yet been transcribed in Braille. Recent advances in sensors, actuators, and microprocessor technology have allowed more sophisticated systems to be developed.

Augmenting Low-Tech Tangible Media

Traditional, tangible diagrams have been enhanced through the use of digital technology, for example, the "Nomad" system [8]. This used a touch tablet in conjunction with a raised paper diagram of a map. The tactile information could be supplemented with audio and speech cues that were triggered by pressing on the tablet. Dynamic audio feedback allows hierarchical information to be stored, and prevents the tactile information from being otherwise cluttered with Braille labels. More recently, the T3 system has applied this technique to create teaching media, including a world atlas, where a student interacts with a tactile raised paper map in order to obtain information about countries of the world via synthetic speech [12].

Systems such as the Nomad combine the benefits of a tangible overview with the detailed information provided by speech. One drawback is that to create new content, the tangible raised paper diagrams still need to be formatted and produced, which often requires a sighted person's assistance. Applications such as maps are relatively static, but the drawback of slow reproduction is exacerbated if the data needs to be updated frequently, as may be the case with visualisations of numerical data. Switching between different representations of data is also problematic, for example, if the user decided a line graph would be a more suitable representation to use than a pie chart. Content needs to be created and manufactured for each individual representation, which could be laborious.

Force-Feedback

Force-feedback devices have also been employed to make visualisations and graphs more accessible to the visually impaired. These devices render 2D or 3D touchable models through programmable constraint forces, conveyed by an armature of one or more degrees of freedom, for example, the series of Phantom devices (www.sensable.com) [7]. The first example of work in this area was reported by Fritz and Barner, who used a Phantom to present line graphs [3]. The most extensive body of work was the Multivis project (www.multivis.org). Results from this project showed that blind people were able to apprehend visualisations such as bar charts and line graphs presented using force-feedback devices, and answer questions regarding the data presented. A multimodal representation using audio and haptic cues was the most beneficial representation [14].

One of the main drawbacks of force feedback devices is that most of them render forces based on a "point interaction" model of contact with the virtual models. This means that the user is represented only by a single point in the virtual environment, typically the tip of a probe or handle with which the user interacts at the distal point of the interface mechanism. Therefore, the user is denied the rich, spatially varying cues that are obtained when exploring a tactile diagram with the whole of both hands; instead, the sensation is more equivalent to poking a diagram with a stick. Due to the lack of spatially distributed cues, perception of shape is slower and more memory intensive, as the user must integrate temporally varying cues in order to build up an overview of the scene [4].

The point interaction metaphor does not preserve the affordances of traditional raised paper format as it constrains the exploration of the user. Further, the devices required are very expensive for an individual. There is also a safety issue to be considered when a visually impaired person is interacting with an actuated and potentially unstable device.

Tactile Feedback

Tactile displays present information to the user's skin via one or more smaller actuators [6]. They are often cheaper, smaller and less intrusive than force-feedback devices. The VTPlayer mouse (www.virtouch2.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 that deliver stimulation to the fingertips (Figure 3). The pins do not vibrate and provide a steady indentation of the skin. They can be raised or lowered, but do not provide any resolution between this. 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.

Figure 3: The VTPlayer tactile mouse. A tactile display with two 4 by 4 arrays of pins.

Jansson and Pedersen studied the performance of visually impaired users browsing a map with the VTPlayer. They observed that tactile information which indicated the crossing of borders on the map had no effect on performance in a navigation task, when used to supplement audio cues. The visually impaired users had many problems using the mouse, as it was an unfamiliar device to them. Mouse use is very difficult without any contextual information on target location when moving. The tactile arrays are too small to allow this type of movement planning. Further, in the absence of continuous visual feedback, the effects of unintentional rotations or lifting of the mouse go un-noticed [5]. Wall and Brewster also observed in studies with the VTPlayer that the size and resolution of the array was too small to allow the users to plan their movements in a manner analogous to that of a sighted user using visual information [11].

REQUIREMENTS CAPTURE

Prior to development of the interface we conducted a requirements capture with visually impaired participants to inform the initial design. Digital representations of data visualisations present several potential advantages: they can be easily stored, quickly manipulated and efficiently distributed, overcoming many limitations of tangible "hard copies" of graphs and visualisations. However, in transferring to a digital representation, we also want to preserve the advantages of low-tech tangible representations currently used by visually impaired people. In transferring to novel digital tools, it would be beneficial to allow users to transfer the knowledge and skills they have obtained working with currently available tools.

Four visually impaired participants took part in an interview, and eight visually impaired people participated in a focus group to identify current tools and techniques for exploring visualisations. Both activities were held at the Royal National College for the Blind in Hereford, England, during March 2005. The most common tools that were reported by visually impaired learners were a combination of heat-raised paper diagrams (Figure 4), and cork boards with pins (Figure 5).The following guidelines were extracted from transcriptions of the interviews and the focus group.. A more extensive description of the procedure and outcomes of the interviews can be found in [11].

Promote rapid, non-sequential access to data

Tangible media allow the visualisation to be explored fully with both hands, which allows the user to quickly get an overview of the data and make comparisons between multiple points. This is especially advantageous when compared to the laborious, serial method used with screen reading software, where the data series must be navigated through in order, and each data point comprehended individually. By contrast, tangible representations support rapid, non-sequential, if slightly less detailed, browsing.

Resources should be easily obtainable and unambiguous

Important landmarks and resources, such as axes and legends can be made to stand out, allowing the user to quickly locate them within the graph and ground their subsequent exploration. For example, in Figure 5, the origin has been "highlighted" by the use of a pin with a larger head than the data points. Also note that the axes have a thicker and higher tangible relief than the gridlines, allowing them to be disambiguated.

The height of a tactile relief can be used to encode the salience of the information represented [2]. Heat raised paper representations are often modified or augmented with adhesive media, in order to increase the height of the tactile relief to make it "pop out" to the user. For example, a data series of particular interest could be "highlighted" to a user in this fashion. Textures or patterns with a lower tangible relief can be used to make different areas of a graph or chart discriminable by touch, analogous to the use of colour in a visual graph. Wall and Brewster noted that providing height cues was difficult with existing tactile displays such as the VTPlayer, due to the lack of control over pin amplitude [11].

Allow external memory use

The persistence of the tangible representation also supports the use of external memory when browsing data sets. When browsing a large amount of information, a sighted person will often mark a place with their finger, make a note in the margin, underline or otherwise highlight visually [15]. With a tangible representation of data, a visually impaired person can also mark the data by placing a finger, or by affixing some other marker. This frees up working memory and makes returning to points of interest in the data quicker, as the sheet can easily be scanned with both hands for markers.

Preserve the layout and structure of sighted visualisations

Although the graphs most likely need to be modified from the visual representation for representation in tangible media, they often preserve the basic format and layout, as well as the underlying data (e.g. order of bars, labels of axes) which facilitates communication and collaboration with sighted colleagues through a shared representation. In comparison, screen readers present graphs as a sequential list of numbers, giving little indication of the layout or structure of a visualisation. Understanding of the visual representation of the data is important, as a visually impaired student may have to construct a graph for an exam question, or may be presented with a graphical representation without access to the underlying data, therefore the format needs to be learned and understood during education. As illustrated in Figures 4 and 5, the graphs are visually recognisable as a bar chart and scatter plot respectively, despite the use of visually impaired conventions, such as the Braille labels in Figure 4.

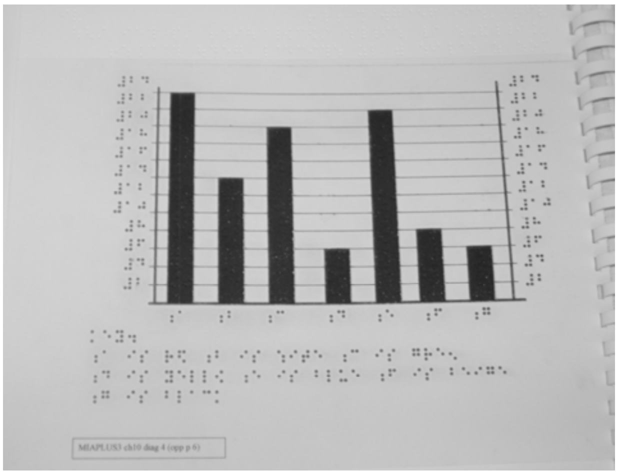

Figure 4: A heat-raised paper representation of a bar graph.

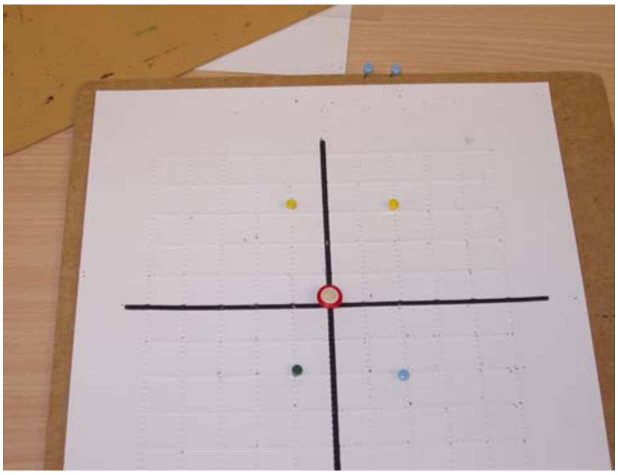

Figure 5: Pin and corkboard representation of a scatter plot. Elastic bands can be wound around the pins to create line graphs.

THE TAC-TILES SYSTEM

Based on the above findings extracted from the requirements capture, we sought to design a tool for browsing visualisations that preserved these advantages in the representation that was employed. We opted to design the system based around dynamic tactile feedback provided by pin-array technology. Tactile displays are smaller and cheaper than force feedback devices, and many have been designed with desktop use in mind (for example, the VTPlayer, Figure 3). They also provide a distributed representation on the skin that is not available with force feedback devices using the point interaction metaphor. As tactile displays such as the VTPlayer have recently become commercially available, it is also salient to research how they might be employed effectively at the user interface.

The Tac-Tiles system seeks to combine the benefits of being able to work in a digital medium with the affordances of low-tech tangible representations of data for visually impaired people. Tac-tiles is built around a tangible augmented WACOM Intuos-3 graphics tablet (www.wacom.com), and a dynamic tactile display. The user browses the graph by providing input with the WACOM stylus in the dominant hand, while the non-dominant hand receives feedback from a tactile array (Figure 1). Tactile output is provided by the tactile display of a Virtouch VTPlayer (Figure 3). The mouse input from the device is disabled, and the device is simply held static with the non-dominant hand to receive tactile feedback to the fingertips.

An overlay tile was created to provide tangible guides which allow the visually impaired user to quickly orient themselves with the layout of the visualisation, and identify important resources which ground subsequent exploration. Presenting these as a physical relief helps the user quickly find them and disambiguate them from the cues presented via the tactile array [11].

It is envisaged that the complete system will support several different representations of the underlying data, and the visually impaired user can switch between them by placing the relevant overlay on the tablet. This could be detected by the controlling software using technology such as Radio Frequency Identification (RFID) tags. When multiple overlays are used, they can communicate their purpose non-visually, by allowing the visually impaired user to explore the relief via touch. This design feature was in particular inspired by the DataTiles system of Rekimoto et al., which used tagged, transparent overlays as a modular interface to applications and data [9].

A prototype system was developed to support browsing of pie charts. We now consider the contribution of the system components to the overall design strategy.

Graphics Tablet

The use of a graphics tablet provides a persistent frame of reference that is not supported with traditional mouse input. The use of graphics tablets by visually impaired users was first proposed by Vanderheiden [10]. Previous studies with the VTPlayer device have shown that the size and resolution of the tactile displays are not sufficient to support a “direct manipulation” style of interaction, such as a desktop or a “graphical user interface” presented through the tactile display [5, 11]. The graphics tablet acts as an absolute positioning device, and therefore adds some context to the visually impaired person’s exploration. As with a paper based representation, a user can employ a combination of proprioceptive and kinaesthetic cues to state with confidence their relative position on the page (e.g. “I’m in the top-left quarter of the pie chart.”). The persistence of physical markers placed on the tablet, such as spare fingers, tokens etc., allows external memory to be employed when working memory is overloaded. Thus, by marking a position on the tablet, the user can quickly return to points of interest.

Tangible Overlays

The tangible overlay tile should ideally support rapid acquisition of key resources by the user, and promote an efficient exploration strategy through physical guides and navigation aids. The overlay is completely independent of the data, therefore the same overlay can be used with any pie chart, and a new tangible representation does not need to be created for each data series. Previous work on bar charts used a tangible representation of the X and Y axes to allow the user to quickly discern the likely position of the bars [11]. Initial designs to support pie chart browsing consisted of a relief of concentric circles. Circular motions are difficult to reproduce free-hand, and the relief makes this easier by constraining stylus movement. If the user favours speed over accuracy, they can choose to use one of the smaller circles. The larger circles are slower to move around, but project larger angles for each slice, which may make estimation of angles more accurate.

The system was prototyped by affixing two compact discs to the surface of the tablet (see Figure 1). The edge of the larger compact disc gave a circular relief of radius approximately 6cm. The smaller compact disc gave a circular relief of radius approximately 4cm. The user could also place the pen in the centre hole of the two discs (arranged concentrically) to give a relief of radius approximately 0.7cm. Small adhesive markers were attached each 90 degrees round the disc, in order to aid with estimation of angles by dividing the whole circle in to quarters.

Tactile Display

The visualisation of the underlying numerical data, is represented using the dynamic tactile display of the VTPlayer. Therefore, a new tactile representation does not have to be produced for each modification of the data, thus speeding up the process of browsing data, and allowing the visually impaired user to become more independent, as they do not require a sighted person’s assistance to create a new representation. The tactile cues aid with navigation and indirect access to the data. In the pie chart representation the user feels when they traverse the edge of a section. The pins on the VTPlayer array are raised as the cursor (controlled by the graphics tablet stylus) passes over the edges of the pie chart sections. One pin on the VTPlayer display corresponds to one pixel on the screen, thus a direct mapping of the visual image to a tactile representation is achieved. Thus, the user can feel an area of 8 pixel width and 4 pixel height directly surrounding the cursor. The lines representing the edge of each segment are 5 pixels wide.

The tactile feedback therefore provides a cue that the user has traversed in to another section of the pie, and can also be used to infer the data value by estimating the distance between edges rendered in this way.

As the VTPlayer tactile displays are controlled by pixel intensity information, there is an accompanying graphical representation of the pie chart that a sighted colleague or teacher can refer to when working with the visually impaired user (Figure 6).

Speech and Non-Speech Feedback

Synthetic speech is a very common means of delivering information to visually impaired users. It can be used to represent text labels and exact data values without cluttering the tactile image with Braille or raised letter representations. The user clicks the button on the stylus to receive context specific information, depending on their location. The speech will tell the user if they are outside the area of the pie chart. If they are on a section of the chart, it will speak the name of the section, the actual value, and the proportion of the whole as a percentage figure.

Speech is very good for detailed information, but it can be laborious and time consuming to listen to and compare many values through speech alone. The use of the graphics tablet partly alleviates this by providing non-sequential access to the data. The user not have to listen to all the section details sequentially, but can employ a “hunt and peck” style strategy to find the months they are interested in.

Non-speech information is better at providing an overview of the data, as it can be delivered in a shorter time than synthetic speech. Encoding the data value in the pitch of a MIDI note is a common sonification strategy used to represent relative values of numerical data. A MIDI note is automatically played when the user traverses the edge of a pie section. The pitch of the note is proportional to the percentage value of the section, thus, a user can quickly scan the chart to get a good idea of the overall distribution of the data, without having to commit the exact values to memory. The notes are 200 millisecond duration, using the general MIDI acoustic grand piano instrument (instrument 0). The highest value in the graph corresponded to MIDI note 100, the lowest value in the graph corresponded to MIDI note 35, with the rest of the notes scaled linearly in-between.

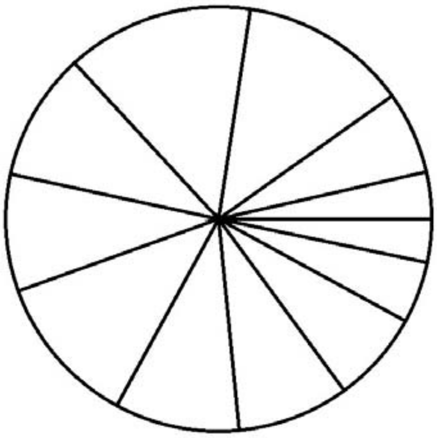

Figure 6: Example of a visual representation of a pie chart displayed on screen. The tactile display pins are raised when the cursor moves over the black lines.

EVALUATION

The prototype system was evaluated with visually impaired participants recruited from the Royal National College for the Blind in Hereford, England, in March 2006. The purpose of the evaluation was to gather qualitative feedback regarding the prototype, in order to suggest guidelines for refining the design of pie chart browsing for the complete Tac-tiles system.

Demographic Information

Six visually impaired participants took part in the experiment. Five were students at the college, studying a variety of higher education courses, one participant was a member of the staff involved in Braille transcription of documents. The age of participants was in the range 16-55 years old, with a mean age of 31. All reported using computers on a daily basis. The most common applications were MS Office (Word being the most popular component) and internet browsers. Two participants were congenitally blind, the other four were late blind. Two participants (including one of the congenitally blind) had no residual vision, the other four participants had varying degrees of residual vision. However, all used accessibility aids to work with a computer, favouring the Jaws screen reader software (www.freedomscientific.com). All the participants had taken part in previous evaluations of multimodal accessibility aids conducted in November 2005, and so were familiar with the procedure and equipment involved.

Procedure

The evaluations were structured around a series of simple exercises with sample pie charts, constructed by the experimenter beforehand. This was to stimulate opinions on the utility of the method of interaction and different feedback modalities in the system. Initially, the participant was asked to supply demographic information, such as age, level of computer use, the courses they were studying at the college, and a history of their visual impairment, including details of any residual vision. The participant was free to withhold any of this information, but none chose to do so.

The experimenter introduced the concept of pie charts by analogy to a heat-raised paper chart which the participant was free to explore. The different components of the system were then introduced, and a practice pie chart was presented to the participant.

All the participants completed the practice pie chart, and then a further seven charts under test conditions. Each pie chart represented the total rainfall in a year for a particular city of the world (selected from www.worldclimate.com). The chart was divided in to 12 portions, each representing a month of the year. This was in the same order for each of the pie charts presented; therefore there may have been an effect of learning during the study. For each pie chart, the participant was asked to identify the largest and smallest slices of the pie (corresponding to the month with highest and lowest rainfalls), and report them verbally to the experimenter, who would make a note of the response. There were therefore 14 questions per participant.

An audio recording was made of the entire evaluation, and later transcribed by the experimenter for analysis. The participants were encouraged to verbally describe any problems they had with the system during operation. For this reason, performance was not timed, to alleviate time pressure and allow the participants to articulate their views clearly, and be questioned by the experimenter when clarification was needed. For this reason we did not measure the time to complete the tasks, as this would be confounded by the amount of dialogue between the participant and the experimenter.

After completion of the seven test pie charts, the participants were also interviewed to gather more feedback on the system. The participants were asked to summarise the strategy they used to answer the questions. The experimenter then drew attention to the individual components of the system (the pen, tablet and overlay; the speech feedback; the tactile feedback; the non-speech audio) in order to ascertain how the participant used each type of feedback to answer the questions. Finally, the participant was asked to summarise by giving the three best and three worst points regarding the system.

Results

Collating the results of the participants, there was a total of 84 question and response pairs. 75 questions (89%) were answered correctly, and 9 were answered incorrectly (11%). Four of the mistakes were due to mishearing the screen reader. Three errors occurred when the values of two slices were very similar. Two errors occurred when a participant confused the pitch mapping, subverting the high and low values.

The recordings of the dialogue between the participant and experimenter, and the post-hoc interviews were transcribed for analysis to identify common strategies employed by the participants during the tasks, and isolate any problems that occurred with the interface. The results of this are summarised below, for each component of the system.

Tangible Guides

All the participants made use of the tangible, circular guides to navigate the pie chart. Three of the participants openly remarked on their effectiveness, and speculated as to the high difficulty without the overlay. Participants generally chose one of the concentric circles that they were comfortable with. All of them chose the outer or middle circle (4cm and 6cm radius), none used the inner circle (0.7cm radius). Two participants adopted the strategy of moving to the outer circle when the angles of slices were small and precise movement was required. The problem most commonly reported (by four of the participants) was that there was very little friction between the pen and the surface, and it was quite easy to slip between pie chart segments. This exacerbated the difficulty of clicking on small targets. Various solutions were proposed. Three of the participants suggested that a groove would help constrain movements better. One participant suggested a zoom function. One participant also suggested dispensing with the visual convention of scaling the segment angles: a visually impaired user would be able to obtain the relevant information from the sonification and speech information without recourse to the angles.

Speech Feedback

There were two common problems with the speech: clarity, and the amount of information that was delivered. The lack of clarity of the speech presented several problems for the participants. Four of the participants suggested that the speech clarity could be improved. In particular there was some confusion between “January” and “February” which led to some erroneous answers to questions. A further participant found the monotony of the voice made it hard to remember values effectively. The second problem with the speech was the amount of information delivered. Two of the participants were not clear on the meaning of the proportion value and had to be instructed by the experimenter. Many participants worked from only one measure, either the value or the proportion. Several participants took to interrupting the speech before it could deliver the second part of the information, as the on-going speech made concentration difficult.

Despite these issues, the speech was found to be an essential part of the system by all participants. It was used to get an exact value for each chart segment, which was important to verify the answers to the questions with a high degree of accuracy. Participants were impressed with the accuracy of the system, and felt that access to the exact values provided a clearer mental picture than having to estimate angles from a raised-paper representation or an image (for those with residual vision).

Tactile

Two participants found the tactile display useful when segments were very small and the borders were close together. It helped them ascertain this fact quickly and gave a strong mental picture of the tightly packed borders. However, none of the participants could exactly state what the tactile information contributed to their understanding of the chart. In fact, most of the participants had to be reminded at some point to place their non-dominant hand back on the tactile display. One participant used their non-dominant hand to locate the guides initially and orient themselves on the tablet, a second participant used a two handed grip on the pen to stabilise their grasp while clicking the button, the others did not use their hand for any discernible purpose.

The confusion over the purpose of the tactile display probably arose due to the redundant nature of the cues. The sonification was used as a cue that participants had traversed the border of a segment, as it was delivered at exactly the same time as the tactile information. Suggested improvements were encoding values in the tactile representation, for hearing impaired users who might not have access to synthetic speech or the sonification, and mounting the feedback in the pen so attention did not have to be divided between the two hands.

Non-speech audio

The immediate nature of the interactive sonification was quickly grasped by the majority of the participants. All but one of the participants followed the same strategy: browse the pie chart by moving around the circle and listening to the sonification in order to get an impression of where high and low values were located. Once several candidates for the highest/lowest value had been identified, further clarification could be requested using the speech audio. The sonification could quickly be used to identify low and high values with ease, although if values were very similar, it was impossible to discriminate the pitches, due to the scaling method used. In this case the participants used speech to discriminate between the values. Only one participant did not use the audio information in this manner, and instead listened to all the values using synthetic speech, sequentially. The audio cues were still useful as a notification of crossing a border between two regions, in this case.

Discussion

The results suggest several potential refinements to the system. These results are presented as more general guidelines that may be applicable to multimodal solutions for visually impaired access to other applications, although they will need to be independently verified for effectiveness in other applications.

1. *Use grooves rather than a relief to constrain exploration*: While the tangible relief was useful, the users had problems holding the pen steady, especially when clicking the button to access speech. A groove that the tip of the pen slipped into would constrain the user to a circular track, affording them quicker and more stable exploration. This guideline also applies to “virtual” interactions with a stylus: similar findings were noted by Yu et al. when using force-feedback devices to explore bar charts with a Phantom[13]. More specifically to the pie chart application, as the smallest (0.7cm) circle was never used, this could be removed from the design. A larger radius circular track could be added in an attempt to exaggerate any potential benefit of a larger projected angle from the pie.
2. *Use clear and concise speech to deliver detailed information on demand*: The speech information is so fundamental to blind users that they will rapidly identify any short-comings. Problems with speech clarity can undermine the performance of a system as a whole. Clarity of speech was responsible for at least 44% of the erroneous responses given to questions. The speech should not deliver too much information, as this could distract the user and overload working memory. As such, the user should be able to cancel the speech on demand. In the case of pie charts, listening to the value and the proportion was quite demanding for the users. Future versions of the system will give proportion information only, as this is the essence of the pie chart representation. The user could request the additional information on exact value, or instead switch to a bar chart representation.
3. *Interactive sonification is an effective means of providing an overview*: The non-speech audio cues were used by all except one user to quickly browse the pie chart and identify a narrow set of candidate answers to a question. The immediate and interactive nature of the sonification appears to have been key to promoting its use. Relating the audio feedback to kinesthetic and proprioceptive feedback obtained through moving the pen helped the user to identify candidate areas of the chart to refine their search.
4. *Tactile feedback may communicate a pictorial impression:* Most users employed the non-speech audio as a cue indicating they had traversed a border on the chart, therefore the tactile information was redundant for this purpose. The users were already attending to the sonification to apprehend the values of the sections, which may be why it dominated the tactile information. Two of the users picked up on the “pictorial” nature of the rendering: when narrow segments were located adjacently in the chart they could apprehend this through the high density of raised pins corresponding to the many borders. This use of tactile feedback needs to be investigated further: the questions in this study were perhaps not the most appropriate to highlight this potential use. Also, due to the redundancy in the cues provided with non-speech and tactile feedback, we cannot reliably claim whether the tactile information was used for the above purpose, and further studies will need to be conducted to verify this.

CONCLUSIONS AND FUTURE WORK

Traditional low-tech tangible media for visually impaired people provides several advantages for accessing graphical information, that are not preserved by current computer-based representations, such as screen reader software. Tactiles is a system that attempts to preserve these affordances, and integrate them with the benefits of an interactive, computer based solution. With future refinements of the system, it is envisaged that the system may promote independence in blind learners by allowing a user to quickly instantiate and browse visualisations using their senses of hearing and touch, without requiring a sighted person’s assistance to generate representations.

The use of a graphics tablet and stylus as an input device preserves the spatial cues obtained through traditional tangible representations, providing context by allowing kinaesthetic and proprioceptive feedback to be employed during exploration. The use of a tangible overlay allows important references, in this case, the circumference of the pie chart, to be disambiguated from the dynamic tactile cues. This may promote communication and collaboration with sighted colleagues by using a tactile representation that preserves the order and layout of the visual representation. Detailed information can be delivered by synthetic speech, and non-speech sounds can be used to provide a quick overview.

In future work, it is planned to conduct a quantitative evaluation to investigate the relative contribution of the different components of the system. In particular, the role of tactile feedback needs to be addressed further. Despite the redundant nature of the cues, tactile feedback may still be important to the system, as there are many situations in which audio feedback may be difficult or inappropriate to use. For example, in a classroom or lecture where the student must listen to verbal instructions or descriptions from a teacher, it would be inappropriate to have audio output which may disturb the other students. Wearing headphones may be problematic, as this may occlude the teacher's speech. In a formal meeting, audio feedback could detract from a visually impaired participant's ability to contribute to discussions. Related sensory impairments are also common in the V.I. community, including hearing, which could render the audio cues difficult to use, or impossible for the profoundly deaf. Similarly, tactile sensitivity can also be impaired by old age or diabetes, so it is important to make provision for redundant information to be delivered to both senses. Future experiments will investigate the role of each method of feedback in the acquisition of data, by testing and comparing different combinations of feedback.

The complete Tac-tiles system is still a work in progress. Currently we have developed representations for bar graphs and pie charts. The next stage in the development will be to develop a multimodal (tactile and audio) representation for line graphs, and an accompanying tangible overlay tile. For the complete system, the tiles will be instrumented with Phidget RFID tags (www.phidgets.com). The software will be able to uniquely identify which tile has been placed on the tablet. The tiles are therefore used as a tangible interface to control the representation of the underlying data. For example, if the user was interested in interpolating between data points, they would use the line graph representation. If they were interested in the different values as proportions of a whole, they would use the pie chart tile. It is envisaged that this will promote greater independence in blind learners studying for numerate disciplines, and make the previously inaccessible study of graphs and visualisations more fun and engaging for the user.

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