Providing external memory aids in haptic visualisations for blind computer users

S A Wall[1] and S Brewster[2]

Glasgow Interactive Systems Group, Department of Computing Science, University of Glasgow,
17 Lilybank Gardens, Glasgow, G12 8QQ, UK

[1]steven@dcs.gla.ac.uk, [2]stephen@dcs.gla.ac.uk

www.multivis.org

ABSTRACT

Haptic force feedback devices can be used to allow visually impaired computer users to explore visualisations of numerical data using their sense of touch. However, exploration can often be time consuming and laborious due to the "point interaction" nature of most force feedback devices, which constrains interaction to the tip of a probe used to explore the haptic virtual environment. When exploring large or complex visualisations, this can place considerable demands on short term memory usage. In this respect, a fundamental problem faced by blind users is that there is no way to mark points of interest or to harness external memory, in a similar way in which a sighted person may mark a graph or table at a point of interest, or leave a note in a margin. This paper describes the design, implementation and evaluation of external memory aids for exploring haptic graphs. The memory aids are "beacons" which can be used to mark, and subsequently return to, a point of interest on the graph. Qualitative evaluation by visually impaired users showed that external memory aids are a potentially useful tool. The most commonly reported problem was that of using the keyboard to control placing of the beacons. Suggestions for subsequent re-design of the beacons in light of the participants' comments are considered.

1. INTRODUCTION

Understanding and manipulating information using visualisations such as graphs, tables, bar charts and 3-dimensional (3D) plots is a very common task for sighted people. The skills needed are learned early in school and then used throughout life, for example, in analysing information, creating presentations to show to others, or for managing home finances. The basic skills needed for creating and manipulating graphs are necessary for all parts of education and employment. Blind people have very restricted access to information presented in these visual ways. It is currently very hard for them to create, manipulate and communicate visualisations such as graphs and tables. As Wies *et al.* state "Inaccessibility of instructional materials, media, and technologies used in science, engineering, and mathematics education severely restricts the ability of students with little or no sight to excel in these disciplines. Curricular barriers deny the world access to this pool of potential talent, and limit individuals' freedom to pursue technical careers" (Wies et al., 2001). Traditional methods of presenting visualisations to blind and visually impaired people include Braille diagrams, heat-raised paper, screen readers and screen magnifiers. There are several drawbacks inherent with these methods in that they are either unable to respond quickly to dynamic changes in data (hard copies need to be produced of Braille and heat raised diagrams which is often slow and difficult for a blind person without sighted assistance), they are inherently serial in nature and therefore highly memory intensive (e.g. a screen reader reading values from a graph or a Braille table), use an abridged form of the data (pre-recorded descriptions of graphs delivered via spoken word or Braille versions of tables), or are simply inaccessible to potential users (only 26% of visually impaired university students read Braille, and screen magnifiers are useless to those with no residual vision).

It is increasingly important to provide fast and reliable access for visually impaired people to the proliferation of digitally stored data, including that which is available on the internet. The EPSRC-funded Multivis project is a collaboration between the Departments of Computing Science and Psychology at the University of Glasgow investigating tools to allow visually impaired people access to data visualisations.

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Techniques from virtual reality are used to present the data using multiple modalities, in particular, haptics and audio. Haptic force feedback devices and tactile displays potentially provide a richer method of interacting with digitally stored data than those currently available to blind persons. Using a haptic device, a blind person could edit and perceive data in real time, whilst working alongside sighted colleagues. Many of these devices have been designed with the desktop in mind (for example, the desktop PHANToM from Sensable Technologies). Some mouse type devices are small and discrete enough to pass as standard computer mice (the Wingman force-feedback mouse from Logitech, or the Virtouch VTPlayer mouse). Work on the Multivis project has extensively employed the PHANToM force feedback haptic interface (See Figure 1). It consists of a kinematic framework with three rotational degrees of freedom, allowing for exploration of a 3D Cartesian workspace (13x18x25 cm). The user interacts with the device by gripping a stylus attached to the distal point of the framework. The device is nominally passive (it does not resist the motion of the user), but motors located on each of the joints can be selectively activated to convey the illusion of contact with a rigid surface.

Figure 1. *The PHANToM haptic interface from Sensable. The user grips the stylus to interact with the device. Movement of the framework is selectively constrained to portray the illusion of contact.*

Previous research has shown that in the absence of visual information, users are able to perceive and interpret multimodal (haptic and audio) representations of common graph types such as line graphs, bar charts and pie charts. Experimental results showed that a multimodal representation of line graphs was significantly more accurate than a raised paper based representation, however, exploration times were significantly slower (Yu et al., 2002). This increase in time was attributed to the point interaction nature of the PHANToM. Limiting the user to a single point of contact precludes the use of Exploratory Procedures (Lederman and Klatzky, 1987) such as enclosure and contour following that are important for perceiving size and shape of objects efficiently (an essential action for comprehending the data in graphs). The lack of spatially distributed cutaneous information on the finger tip means that the users instead have to integrate a series of temporally varying cues as they traverse the graph. Exploration is therefore slow and highly memory intensive as little context can be provided through a single point of stimulation. These problems are further exacerbated when dealing with large data sets or data exhibiting a high dimensionality.

A fundamental problem faced by blind people when interacting with visualisations (or any complex information) is that there is no easy way to mark points of interest or to access external memory (Zhang and Norman, 1994); a sighted user might mark a graph with a pen to indicate an interesting point to return to later, or write something in the margin as a reminder. Such external memory is a very powerful tool for sighted people and can significantly reduce working memory requirements. This is not possible for blind people and means that they may easily get lost in the data, overloaded, and makes it hard for them to mark interesting points in the data. This slows down interaction, increases workload and means that it is more likely that mistakes will be made. As Stevens suggests, providing access to an external memory aid will give very substantial benefits to blind users (Stevens, 1996). This paper describes the design and evaluation of an external memory aid for blind and visually impaired users accessing complex visualisations using a PHANToM force feedback device.

2. INTITIAL DESIGNS

This section describes the design of the external memory aids that are proposed. Also provided is a brief description of the haptic graph rendering software, which is necessary to give context to the evaluations in Sections 3 and 4. Readers are referred to the papers referenced herein for a more complete description of the system.

2.1 External Memory Aids

The external memory aids were initially designed to be used with three dimensional surface plots of data rendered using the haptic interface. The PHANToM force feedback device could be used to explore the height and contours of a surface which represented a three dimensional data set, for example, as illustrated in Figure 2. Data were stored in a table for different combinations of x and y values. The height of the surface on the z axis is proportional to the value of the data for that combination of x and y. The large surface area of the plot could potentially present spatial memory problems for a visually impaired person exploring through the single point of contact offered by the haptic device.

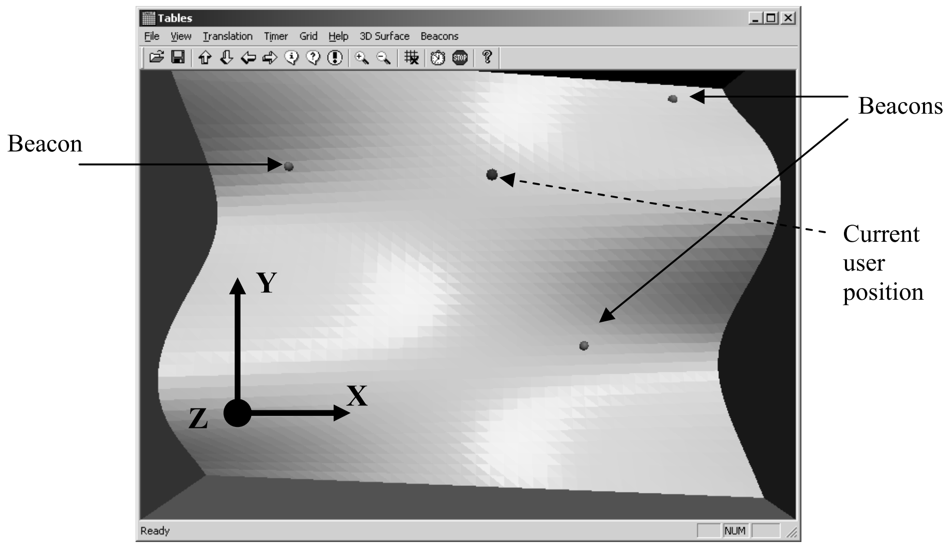

Figure 2. *Screen snapshot of a haptic surface plot with visual representation of beacons. The user can feel the 3D surface of the table using a PHANToM haptic interface. The value of each cell is mapped to height in the z- direction.*

The initial design of an external memory aid consisted of multimodal beacons using haptic and audio cues. By positioning the PHANToM at a point of interest on the 3D plot and issuing the appropriate command (via a key press) a beacon could be enabled at that point (see Figure 2). There were three beacons available to the user; one beacon was assigned to each of the keys “a”, “s” and “d”, and was enabled by pressing the relevant key. Users could subsequently return to a beacon they had placed by pressing the relevant key again, along with the “shift” key, to access a “seek” mode for that beacon. This caused the PHANToM to guide users to the beacon’s location, by actively dragging them from their current position to the position of the beacon, using a virtual spring force. The keys used to control the beacons were chosen so that they could be used with the non-dominant hand, while grasping the PHANToM stylus with the dominant hand. Thus, having identified a salient point on the graph, for example, a local minimum, should the user find a second local minimum, he/she can easily compare the two without devoting time to relocating the original point. Non-speech audio MIDI percussion sounds were used to represent the beacons. The beacons were differentiated by each using a different timbre. The audio was panned to the right or left relative to the current position of the PHANToM end point. The volume decreased exponentially with distance from the beacon. This helped provide some context regarding the relationship between the user’s current point and any points of interest he/she may have marked.

2.2 Haptic Bar Charts

As the haptic surface plots have not yet been formally evaluated with visually impaired users, we opted to perform evaluations of the beacons using existing software for rendering haptic bar charts. These have been tested several times with visually impaired users and have been shown to be a robust design (Yu and Brewster, 2003). As the main purpose of this investigation was to assess the design of the external memory aids, using them with the untested surface plots may have produced experimental difficulties that were attributed to the memory aids themselves, but which were actually flaws in the design of the surface plots. The size of the bar charts was increased from seven bars, used in previous studies, to twelve bars, to increase the associated memory demands.

The virtual bar charts used were rendered using the GHOST SDK from Sensable Technologies as used in previous studies of the Multivis project (Yu and Brewster, 2003). The bars are located on the back wall of the workspace facing the user, as opposed to on the "floor" of the virtual environment, as with traditional raised paper graphs on a desk or table. A snapshot of a graphical representation of this environment is illustrated in Figure 3. The bars are constructed out of polygons that form a V-shaped cross-section. The purpose of the V-shaped channel is to retain the PHANToM pointer within the line. Preliminary studies with haptic line graphs showed that users had problems keeping the pointer on raised objects (Yu et al., 2001). A concave shape is an effective solution to this problem. The user could click the PHANToM stylus switch while in a bar to have the label for the bar read out (a text label describing the bar provided in the data file). No information was given on the data value of the bar. There were 12 bars in each chart; the user could thus feel the height of the bars using the PHANToM stylus in order to make a comparison of the heights.

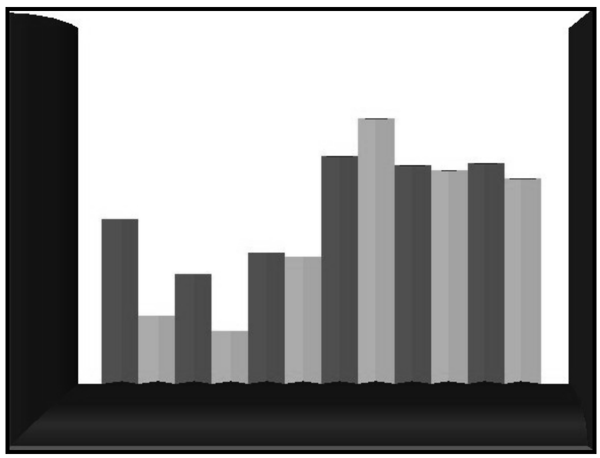

Figure 3. *Visual representation of a haptic bar chart with 12 bars, as used in the evaluation. Bars were rendered as grooves in the surface in order to constrain the user's exploration.*

3. PILOT STUDY

Prior to testing the beacons, an informal pilot evaluation was undertaken with two participants from the University of Glasgow. This study was conducted to evaluate the basic design of the beacons before they were presented to the visually impaired users, and to correct any obvious design flaws. It is important to maximise the productivity of evaluations conducted with visually impaired users; pilot testing with sighted users (in the absence of visual information) is an efficient method of refining the designs of stimuli and experimental procedures. Neither participant was naive to the purpose of the study, and both had full (or corrected) vision. The participants were not blindfolded but were unable to see the monitor displaying the visual representation of the graphs. Both participants were presented with several bar charts and asked some questions on the data to encourage them to use the beacons (the full experimental procedure used in the formal experiment is outlined in Section 4).

Two significant design modifications occurred as a result of the participants' comments. Firstly, it was noted that the users placed the external memory aids less often than they used the "seek" function. The general strategy employed was to place the beacons on the bars of interest and then subsequently use them to jump between the bars and compare the heights. Participants also became frustrated when they moved a beacon by accidentally pressing the "place" button for the beacon more than once. As placing beacons was a less frequent action, the controls were changed so that a modifier key press was needed to place the beacon, and seeking was the default action (enabled by pressing the relevant beacon key alone). This also reduced the chances of accidentally replacing one of the beacons with an erroneous key press. Secondly, the participants found the audio cues from the beacons confusing and distracting to use. As such, the recurrent audio cues were disabled, and instead a percussion noise was played once, to let the users know they had successfully placed a beacon. This revised design of the external memory aids was then evaluated with visually impaired participants.

4. EXPERIMENTAL PROCEDURE

To evaluate the external memory aids, a user-centred experimental design was employed to capture blind and visually impaired users' requirements and opinions. The main purpose of the study was to identify areas in which the design of the beacons could be improved using qualitative data obtained via a *post hoc* interview with the visually impaired participants. To stimulate opinions on the beacons, participants were given tasks to perform in a condition with the beacons, and in a condition where they did not have access to them. The views of the participants could then be used within an iterative design process to create a second, refined version of the beacons.

Eight participants took part in the evaluation. All were registered blind and based at the Royal National College for the Blind in Hereford, UK. They were all paid for their participation in the evaluation. When verbally questioned during briefing on the experimental procedure, all participants said they had prior experience with the concept of bar charts before participating, except for one participant. This participant was shown an example of a tactile raised paper bar chart and had important elements such as bar and axes described verbally by the researcher. The participants were free to ask any questions and gave verbal consent when they felt they had grasped the concepts sufficiently to progress with the evaluation. The participants also had varying degrees of residual vision. Three of the subjects had used the PHANToM before on previous experiments run as part of the project. All subjects were given full instructions on how to operate the PHANToM and given a verbal walkthrough of the elements of a haptic bar chart (as described in Section 2.2) by the researcher.

The two conditions of the study were with and without the external memory aids. The order of these conditions was counterbalanced between participants to control for ordering effects in the data. For the condition incorporating the memory aids, the participants were encouraged to use them to aid their performance. A group of fifteen bar charts were used in the experiment, based on data gathered from National Statistics Online (http://www.statistics.gov.uk/) and WorldClimate (http://www.worldclimate.com/). The same group of fifteen bar charts was used in both conditions of the experiment to prevent any confound due to the relative difficulty of different sets of graphs. To prevent the participants from using prior knowledge obtained during the first condition to aid performance in the second condition, they were told that the graphs represented different information. Thus, in the first condition, the participants were told that the graphs represented monthly coffee export figures for different countries. An example graph from this set is a bar chart showing the average monthly coffee exports for Haiti, with the bars labelled from January to December, or the average coffee exports for the month of June over 12 different countries, the bars being labelled with the country names in alphabetical order from left to right. In the second condition the data were described as weather statistics such as rainfall, temperature and pressure levels from cities around the world. An example bar chart from this set might be the average monthly rainfall for Glasgow, with the bars representing the different months, or the average temperature over 12 cities for a particular month, with the bars labelled with the names of the cities.

There were 15 trials during each of the experimental conditions. In each trial the participant was presented with one of the bar charts in the data set. Prior to its presentation, the participant was told what the bar chart represented (for example, "Coffee exports for Burundi over the months of the year") and given a question to answer as quickly as possible using the information in the bar chart. This question was always of the form of which bar had the highest/lowest value out of three given bars (for example, "During which month were the coffee exports for Burundi highest, out of May, June and October?"). All the information needed to answer the question was contained within the graph. There were no trick questions, and participants were informed that they were not required to answer any further questions regarding the graph and therefore need not concern themselves with any other bars, provided they locate the three salient to the question posed. However, participants were advised that they should check the bars thoroughly, rather than assume the answer from any knowledge they had on the subject of the question. Participants had a 2 minute time limit to answer the question, with a speech audio reminder provided by the software after 1 minute. Participants verbally indicated their answer to the researcher, who immediately stopped the software timer and made a note of the response. The participant was then presented with the next trial in the condition, using the same procedure. The proportion of correct responses and the average time taken to answer each question was used as a measure of performance for the participants in each condition. It was hypothesised that during the condition in which the beacons were used, the participants would perform faster, as they would be able to use the beacons to return quickly to bars salient to the question, in order to make comparisons more swiftly.

A post-experiment interview between the researcher and participant was conducted, during which the participants were invited to give their opinions on the system, and the researcher also questioned them regarding any strategies or behaviours they had employed in use of the external memory aids. All interviews were recorded with participant's consent and later transcribed for analysis.

5. RESULTS

Although the participants were encouraged to use the beacons by the researcher during the relevant condition, ultimately, it was at the participants' discretion as to how much they employed the external memory aids. The frequency with which participants used the beacons varied widely, from regularly to very infrequently. This can be attributed to several factors which varied between individual participants. These were: level of aptitude with the haptic device, degree of residual vision, level of expertise in using the keyboard, and additional impairments related to loss of vision which the researchers had to be sensitive to (e.g. motion impairment in the non-dominant hand used to operate the keyboard). This was potentially compounded by the fact that the beacons were not particularly easy for the participants to use, as their comments revealed during the interviews. Therefore, it was decided that a formal, quantitative analysis of beacon use would not give the most useful data to help refine the design, and analysis therefore focused on the qualitative comments from the interviews.

Averaged over both conditions and across all participants, the proportion of correct responses was 76% (standard deviation = 13) and the average time taken to answer a question was 50.92s (standard deviation = 12.48 s). This illustrates that the participants had little problem answering the questions accurately, and within the time limit set by the researchers, nor was the task so easy that a ceiling of performance level was reached.

From analysis of the transcribed user comments obtained during the interviews, the general feeling of the participants was that the external memory aids were a potentially useful addition to the haptic graphs. The majority of the participants stated they would find the memory aids useful in certain situations, even if they did not employ them extensively during this study. The most common scenarios for use of the memory aids were to avoid searching erroneous bars while traversing large distances between different extremes of the graph:

> *"When two are very similar … it does help to go straight to it, because it's distracting when you look at the height of a country that you don't need."*

> *"If you need to get back, like you're at one end of the track … this thing seems a million miles apart to me because I'm blind, so if you're up in December and you want to go straight to January … in the end I let it go and it went back and found it"*

> *"It was easier when you were moving greater distances, easier with the markers if you were going from one end of the graph to the other, it was more convenient to help you find your place."*

Two of the participants, both of whom had previously participated in experiments using haptic devices (but without the external memory aids), felt that they did not need the external memory aids to perform the task. They both expressed the view that the memory aids would be more useful to beginners finding their way around the graph. Despite this, both concurred independently that the memory aids would potentially be more useful with more complex questions or graphs:

> *"I wouldn't say it would never be useful. It'd be nice to know it was there … if I was looking for information on two things like what are the two highest months of the rainfall."*

> *"I'd say if I had large, four, five or six countries to find, marking the important ones for me might be interesting."*

The most common negative remarks were regarding the use of the keyboard to place the beacons, and the demands on memory associated with use of the beacons. Four of the participants commented directly on the problems associated with using the keyboard at the same time as the PHANToM. Participants found it distracting to use the keyboard whilst attempting to maintain a steady position with the PHANToM stylus on the bar they were exploring. This often led to beacons being placed on bars other than those intended, which was confusing for participants. A salient point was that, despite having the external memory aids introduced to them as "beacons", only two participants explicitly referred to them using this term in the *post hoc* interviews. A further participant referred to using "the keyboard" and only used the term "beacons" after being prompted by the researcher. The remaining participants referred to them as: "keys", "keyboard" or "buttons" (3 participants); "markers" or "marking" (2 participants); no explicit reference (1 participant).

Coupled with the generally low usage of the beacons, this possibly indicates that the participants had difficulty grasping the concept of "beacons" as presented during the study. This may be due to the fact that in other contexts, "beacons" are often auditory or visual in nature, whereas the "beacons" used in this study were neither. This would suggest that a change in name would be useful for further investigations.

Several of the participants indicated that they felt they were able to cope with the memory demands of the questions without recourse to the external memory aids (3 participants). Two of the participants disliked the extra memory demands that were incurred through actually using the beacons:

> *"It would be handy if it told you where you've already placed it …at the moment you're having to use your memory a lot … and then you still have to concentrate on the heights of the rainfalls or whatever."*

> *"Another feature would be to bring up a list of beacons that you've already marked because I sometimes forgot what I'd marked."*

These memory demands seem qualitatively different from participants remembering where bars were spatially, in relation to one another on the graph. This did not seem to pose a problem for most participants; several commented on the fact:

> *" … the second and third time I knew the order of the countries really quickly … If I was to use the beacons a lot, I think that would've held me up more than just letting me get on with using my memory … I could just remember where Haiti was."*

> *"I thought it was interesting how I would just jump to the three countries mentioned or the choices mentioned without knowing the rest of the graph, it was almost like I knew where it was and I've got no sight at all ... I could visualise the graph … I do visualise stuff quite a bit, and that seems to have played a part …"*

One participant likened the memorising of locations of the bars to remembering positions of favourite tracks on a new album:

> *"I soon quickly remembered them, but that made me think of when I play a CD at home and it's the first time … I listen to the whole album all the way through … I remember the tracks as it's running through … I can remember it, and I've only listened to the CD once. That's the same as with countries … I only had to look through that once and I could more or less remember the order …"*

Two participants both suggested that a speech reminder as to where the beacons were placed should be available by pressing an easily accessible button, the space bar, for example.

There were several other comments raised by one or two individual participants that are potentially interesting for influencing a second design iteration of the external memory aids. Two participants commented on the audio feedback. One participant felt that the percussion noise when placing a beacon was not audible enough, and speech output (e.g. "beacon activated") would be better, particularly in a noisy environment such as a classroom or a communal office. The second participant suggested that a different warning noise should be played if the user attempted to place a beacon that had already been placed earlier. With regards to the haptic interface device, one participant indicated a preference for being able to use their fingers to explore the graph rather than the stylus. Similarly, another participant suggested that Braille output for the bar labels might be useful if incorporated in to the PHANToM:

> *"What would be really nifty, is incorporating a small Braille display in to the pen. So as you press the button* [on the stylus] *it pops up under your fingers, "Beijing", or whatever…"*

6. DISCUSSION

Given the participants reported experiences with the external memory aids, it is evident that there are several areas where the design needs to be improved in order to make the potential benefits more accessible. The most significant problem appears to be in the use of the keyboard, simultaneously with the PHANToM stylus. In particular, the use of the arbitrary keys assigned to the beacons, and the use of the modifier key which necessitated two fingered interaction appeared to cause problems. Several participants implicated this as the reason that they chose not to use the beacons regularly, or the reason they found that progress slowed down when they were used. Another potential reason for the low level of beacon use is that the participants found the concept of the "beacons" difficult to grasp. This is demonstrated by the fact that not many participants referred to the beacons directly during the *post hoc* interviews without prompting from the researcher. Several participants chose to describe them in terms of the "buttons" or the "keys". The participants chose to characterise the memory aids by the physical interface, rather than its function within the system, which suggests they may not have fully grasped the potential of the beacons and developed strategies for their use. Despite this, the participants almost unanimously (7 out of 8 participants) thought the external memory aids were potentially useful, in particular for novice users, more complex data, or for traversing large data sets quickly.

An improved design of the beacons should therefore attempt to improve the accessibility of the keyboard interface, leverage the visually impaired users' excellent spatial memory skills, and be conceptually simpler, to suggest a potential model of use to participants. The proposed solution at present is to allow the participants to "snap to" any bar in the chart by pressing a corresponding number on the numeric keypad. Thus, there is no "setting" of beacons, freeing the participants of this aspect of the cognitive load. Most visually impaired users are comfortable with the numeric keypad as it is often employed in screen reading software (for example, JAWS from Freedom Scientific). Provided they remember the relative position of the bar in the graph (something most participants excelled at) they could press the corresponding numeric key to move to the bar. In this way, the system is made more analogous to using a TV or CD player remote control in order to skip to tracks/channels/bars of the user's choice; a concept which most of the users should be familiar with. This would eliminate erroneous placing of memory aids, and the need to remember their positions, whilst allowing the participants to use their spatial memory skills to remember the location of the bars. This method of interaction is less generic and could not be applied to the haptic surface plots without redesign, but could potentially solve many of the problems encountered with bar charts.

7. CONCLUSIONS AND FUTURE WORK

This paper has considered a qualitative evaluation of a preliminary design of external memory aids to be used in haptic bar charts for visually impaired users. The users seemed to appreciate the potential of the memory aids, but their comments revealed several shortcomings of the current design. Participants' comments were used to suggest a further iteration of the design which will attempt to reduce the cognitive load of using the memory aids whilst providing the benefits highlighted by the participants. Future work includes implementing the new design with both bar charts, and more complex 3D surface plots, as originally envisaged. It is also planned to perform a more longitudinal study with the memory aids in order to identify common actions, recurrent problems, potential shortcuts and emergent strategies for use.

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