Constructing sonified haptic line graphs for the blind student: First steps

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Constructing Sonified Haptic Line Graphs for the Blind Student: First Steps

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ABSTRACT

Line graphs stand as an established information visualisation and analysis technique taught at various levels of difficulty according to standard Mathematics curricula. It has been argued that blind individuals cannot use line graphs as a visualisation and analytic tool because they currently primarily exist in the visual medium. The research described in this paper aims at making line graphs accessible to blind students through auditory and haptic media. We describe (1) our design space for representing line graphs, (2) the technology we use to develop our prototypes and (3) the insights from our preliminary work.

KEYWORDS: force feedback, haptic display, line graphs, spatial sound, and visual impairment

INTRODUCTION

This work is being carried out as part of the 3-year MultiVis project. Its aim is to investigate different human sensory modalities to create systems that will make statistical information representations accessible to blind people. In this paper, we focus on line graphs. The opinion that the utility of line graphs to the blind person appears to be contentious is shared by a number of teachers (involved in the teaching of blind students) we interviewed. This proposition is based on the assumption that blind students are not likely to come across line graphs in their daily reality. It is argued that there are other skills that are more relevant to the day-to-day interaction of the blind person. One teacher, suggested for instance, that more time could be invested teaching young blind students to recognise coins by touch rather than teaching them line graphs which they rarely come by or use in practice. While we are sympathetic to this position which essentially reflects the current state of data visualisation tools, we believe that there is no reason why such tools must be predominantly visual. In addition to the fact that blind people need access to graphs for standard technical education, we contend that (1) the usefulness of line graphs is not media dependent and (2) access to the functionality of line graphs can be achieved through non-visual media, more particularly in the auditory and haptic media.

A number of researchers have investigated approaches with varying degrees of success that illustrate how the functionality of line graphs can be made accessible to the blind person. However, the bulk of this research so far has been focused on establishing the *possibility* [sic] of conveying information about line graphs to the blind person. Less evidence exists demonstrating the effectiveness of such techniques to generate analytic tools in casual use by the targeted user group. For example, research results show that sonifying x-y plots by representing the y-value as a changing pitch does convey fairly successfully aspects of the data such as linearity, monotonicity and symmetry (Mansur 1975) but such devices have not progressed easily beyond the labs where they were prototyped. More recent efforts to use tone plots for over viewing data include the Accessible Graphing Calculator that also provides speech output for access to graph information (Sahyun and Gardner 1998),(Bulatov and Gardner 1998). An experiment to evaluate numerical tabular data (300 data values) comprehension tasks using pitch and speech show a significant increase in the number of questions answered correctly (T_{14}=-4.01, $p_{two\text{-}tail}$=0.001) and a significant decrease in the mental load (T_{14}=3.04, $p_{two\text{-}tail}$= 0.009) and frustration (T_{14}=3.19, $p_{two\text{-}tail}$=0.006) of blindfolded users when they are provided opportunities to access data through both pitch representing data (pitch proportional to value) and speech rather than through speech alone (Ramloll 2000).

This approach of transposing visual information into non-visual media has also been used for mapping graphic user interface (GUI) objects. In the experiment set-up by Poll and Eggen (1996), a blind subject uses an absolute mouse to scan for GUI objects represented by speech and non-speech sounds within a rectangular area bounded by standing edges.

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The combination of the absolute mouse position, the constrained area within which the mouse can be positioned and auditory messages allow users to successfully localise GUI objects (Poll and Eggen 1996).

Kennel's (Kennel 1996) work suggests that blind users, within a relatively short time can read simple diagrams with the aid of a touch panel and an associated auditory display. The diagram is displayed on the touch panel; in fact, a sheet of swelling paper covering a tablet, with parts generating relevant auditory messages when touched. The whole diagram can thus be explored using this audio-tactile strategy.

Arguably, in the last two cases the tactile element of each environment is static and can only be used as a passive representative medium. In addition, concerning Poll and Eggen's arrangement, tactile information is only used to give the reader cues about the current absolute position of the mouse on the display but the GUI objects themselves provide no tactile information.

With the increasing availability of force feedback devices, researchers are now showing sustained interest in the design of refreshable or dynamic audio-haptic displays. (Ramstein, Martial et al. 1996) have developed the PC-Access system which they claim offers auditory information (non-verbal sounds and voice synthesis) reinforced by the sense of touch to enhance user productivity, increase their satisfaction and optimise their workload. More recently, [Grabowski, 1998 #19380] have showed the feasibility of using a combination of the sense of touch, using the PHANToM haptic interface, and representative soundscapes to develop visualisation aids for the blind and visually impaired individuals.

OUR DESIGN APPROACH

We adopted a participatory design approach to drive our research project. Its initial phase involved setting up a close interaction network, e.g. regular focus group meetings, between designers, prospective users and institutions such as the Glasgow and West of Scotland Society for the Blind. This network provides opportunities for our target user group to influence the whole design cycle right from the design idea generation phase, through the prototype implementation, to the user-testing phase.

Requirements Capture

Our research began with an initial requirements capture phase that involved visits to institutions involved in educating blind students (Royal Blind School in Edinburgh, Dumbarton Academy in Glasgow and Dundee University). A representative summary of these visits follows keeping in mind that we only focus on class activities relevant to our research agenda. We attended two half-day sessions at the Royal Blind School, Edinburgh and observed blind students being taught line graphs. The students had varying degrees of visual impairment and competence in Maths. There were three students (~10-13 yrs) in the junior group and three other in the senior group (~14-18 yrs). Students in the junior group showed familiarity with simple line graphs, e.g. line graph representing 'money in bank' versus 'time', while the senior group exhibited more complex skills when tackling advanced tasks based on graphs dealing with more abstract variables e.g. parabolic curves illustrating 'instantaneous acceleration' versus 'time'.

Labelling the axes of a simple 2-D graph

The first task set by the teacher for the junior students involved the labelling of the axes of a graph with suitable values. The partially sighted students used ordinary printed-paper while the blind students had access to swelling paper with raised gridlines. The latter made use of a Braille-typewriter to label the axes on the raised paper taking about two minutes to complete the task relying mainly on cutaneous response to identify the intersection points on the grid.

Identifying co-ordinates of pre-defined points on a graph

Following the last exercise, the students were then asked to identify the coordinates of a set of predefined points (Figure 1). The points were represented to the partially sighted students by a prominently printed black cross on the printed grid. For the blind students, the points were represented as a raised round dot on a raised grid paper. The students were largely successful in completing this task. Pre and post-task interviews with the students indicated reliably their understanding of X-Y coordinates.

Figure 1. Identifying co-ordinates of pre-defined points

Constructing a line graph using pins and rubber-bands

In the next task, the students were requested to construct a line graph based on co-ordinates identified in the previous exercise. The tools available included a soft wooden board overlaid with a raised grid A-4 paper, some drawing pins and rubber bands (Figure 2). The students were instructed to insert a pin at the correct point positions on the grid and wrap the rubber bands around the pins to form a tactile line graph. This task proved to be problematic as will be explained shortly and often required the intervention of the teacher for its successful completion.

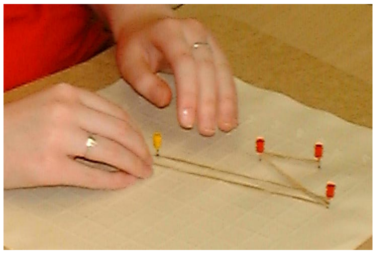

Figure 2. Constructing a 'rubber-band' line graph

A number of problems were observed in this tactile graph construction process. Firstly, blind students have to use one hand to find the points and use the other hand to insert drawing pins in parallel. This procedure can potentially injure their fingers. Secondly, although joining the pins by the rubber band is a good idea, it is not effective for curves with intricate bends. Such situations require several pins to be located closely together to represent the curve at a reasonable degree of accuracy. Lastly wrapping the bands around the pins appropriately is a daunting task because an overview of the graph is not available in the first place.

Lessons from Classroom Participation

Need for non-visual data analysis and inspection tools

It is important to mention at this stage that most students, when asked to feel the 'rubber band graphs', were convinced about the usefulness of line graphs for understanding and 'perceptualising' a data set. In our opinion, this firsthand information from the visually impaired individuals themselves is encouraging as far as they demonstrated an understanding of how a simple data analysis and inspection tool can provide insights into data sets. Similar observations have been made at the other institutions mentioned earlier.

Predominance of tactile data representations

We have observed that currently blind students have access to graphs mainly through the tactile medium. For example, tactile graphics embossers are used frequently in the institutions we visited. The students also have access to books in Braille with tactile graphics describing simple geometric shapes and graphs (Gillepsie 1997). It is interesting to note that the auditory medium, even in the form of simple tone plots, is not as prevalent as the tactile medium as far as data analysis and inspection tools are concerned. We only came across the use of the auditory medium in screen reader applications or talking calculators in the classrooms we had access to.

Construction of tactile data representations

The construction of tactile data representations appears to be time-consuming and does involve a significant cognitive overhead. For example, the construction of rubber-band graphs is by no means easy even if the materials used are easily accessible. The off-line printing of graphs on swelling paper to produce embossed diagrams is also time-consuming. In all these cases we found that the active engagement of a non-visually impaired individual is required to facilitate the creation of these representations. One teacher acknowledged that the time constraints for a mainstream teaching environment are such that she often does not have time to construct tactile graphs which occur frequently in science experiments. While it is currently not technically difficult to make simple tone-plots a feature of a screen reader application this is still challenging to achieve in the haptic medium.

Classrooms tend to be less homogeneous than mainstream ones

Meeting our prospective users has reminded us of a few significant points. Blind people's age, educational background and knowledge of Mathematics will undeniably affect their performance in evaluation experiments. We believe that the perception of graphs probably varies between congenitally and adventitiously blind subjects. Previous evaluations of systems aimed at improving blind users' access to graphs indicate that it is challenging to explain to a congenitally blind person the meaning of x and y axes and the concept of coordinates (Yu, Ramloll et al. 2000). Finding homogeneous groups concerning the degree of visual impairment and education for our experiments is challenging.

Issues when introducing new technologies in the classroom

Coming into contact with our prospective users in their own environments exposed issues arising when assistive technologies are introduced in the classroom. Line graphs are commonly printed on swelling paper in an attempt to make them accessible to the blind reader. However, there are a few problems with this medium. Firstly, it does not provide as many opportunities for interaction in the tactile medium as paper does in the visual medium. For example, it is impossible for an embossed diagram to be zoomed while this is quite possible for a diagram on paper simply by one's eyes closer to it. Also the fact that the creation of a tactile diagram is a laborious process shifts the focus from the data visualisation and inspection task to the creation process. Secondly, the raised features get flattened with frequent use. Thirdly, overviews can be achieved but with much difficulty. In spite of these drawbacks, they are ubiquitous and do not disrupt normal classroom environments. The problem of interactivity can be resolved to a certain extent by a recent innovation and equally ubiquitous device, the Thermo-Pen™ from Repro-Tronics, Inc., designed to assist blind and visually impaired individuals in the creation and understanding of tactile images. However, teachers tend to be cautious about the use of this device especially when children are involved because of the hot-tip which can be touched accidentally. Our interviews with teachers reveal that noisy Braille typewriters are known to be a contributing factor to the exclusion of blind students from a class populated with a majority of students free from major sensory impairments.

Collaboration in non-visual environments

Participating in classrooms for visually impaired students revealed that there is a highly intense spoken interaction between the students and the teacher and, in some cases, between the students themselves during collaborative activities. This increase in spoken interaction is an attempt to bridge the communication gap resulting from the lack of visual cues such as gaze-awareness (known to play an important role in collaborative activities (Ishii and Kobayashi 1992; Gale 1998)). When observing students collaborating on a task involving a common diagram, we found that they frequently tended to speak out their thoughts and the various objects they recognised so as to inform their peers about what they are focussing on. This is an important factor that we need to take into account in the design of our system.

From observations to motivations

In light of these observations, we must therefore ensure that the introduction of the technology that we propose will not disrupt any well-established and utilised modes of communication in the classroom. We are also motivated to achieve user independence by designing a system that will not require the intervention of a sighted helper in order to be used. It is also important that our system encourages users to focus on data comprehension tasks rather than on the construction of the data representations, as is the case with offline printing using embossers or rubber-band graphs. Our force-feedback haptic device to be described shortly allows us to create haptic representations as quickly as visual or auditory ones. We hope that our system will encourage the integration of blind students with their non-impaired counterparts in a common physical study environment so that their learning experiences are shared and enriched.

OVERVIEW OF OUR DEVELOPMENT PLATFORM

The main elements of our development platform are described in Figure 3 and Table 1. Two Pentium III 500 MHz PCs running Windows NT are used, one dedicated to the rendering of the tactile environment (Figure 3, item 3) and the other responsible for producing a high quality spatial sound environment (Figure 3, item 5). The haptic device is a PHANToM 1.5 from SensAble Technologies. The PC used for creating 3D soundscapes (Figure 3, item 5) is fitted with a CP4 Digital Audio Convolution Processor from Lake Technologies. This device is a general-purpose signal-processing engine useful for applications such as complex audio simulation and virtual reality. One of the software packages available with CP4 is the Huron Simulation Tools aimed at designing dynamic virtual sound fields for playback through speakers and headphones. The simulations provide a high degree of realism through the use of proven acoustic modelling methods coupled with Lake DSP's low-latency convolution technology. The 3D sound rendering is based on the source location and angle information, the location and angle information of the listener object and the acoustic properties of the space they inhabit. The modules of applications dealing with the creation of associated soundscapes can connect to and control the CP4 processor using the LakeNet protocol. LakeNet is a collection of command packets which can be sent to a CP4 via a network configured for TCP/IP.

In our case the line graph application resides on the PC responsible for haptic rendering (Figure 3, item 3). This application (Figure 3, item 5) sends LakeNet packets through an Ethernet connection (Figure 3, item 4) to the spatial audio rendering engine running on the other (PC Figure 3, item 5). These packets contain information to position appropriately the sound source and listener associated with the application but existing in the soundscape managed by the PC (Figure 3, item 5) fitted with the CP4 processor. The line graph application also generates MIDI messages that are fed (Figure 3, item 6) into a MIDI synthesiser. The audio output from the latter is fed into the patch bay (Figure 3, item 10) to produce the auditory source for the virtual object associated with the line graph. The precise significance of this virtual source will be described shortly. Signals from the patch bay are then amplified and fed to headphones to present the soundscape to the line graph reader. This arrangement can potentially allow us to represent 8 line graphs (the number of inputs to the patch bay) concurrently each having a particular sound source dedicated to it.

We have adopted this platform for the development of our prototypical line graph reader for a number of reasons. Firstly, distributing the processing load for haptic and 3D audio rendering ensures reasonable synchronisation of renderings in both media so that the virtual environment produced is convincing (Figure 4). Secondly, the software modules that accompany the CP4 provides the opportunity to select an appropriate Head Related Transfer Function (Begault and Wenzel 1991) from a list of standard ones which can be augmented with user specific ones. Since we are committed to use convincing high quality spatial sounds in our prototypes, this facility is essential to the project. Thirdly, the sound rendering in this platform is highly tailorable and can therefore be optimised for a user.

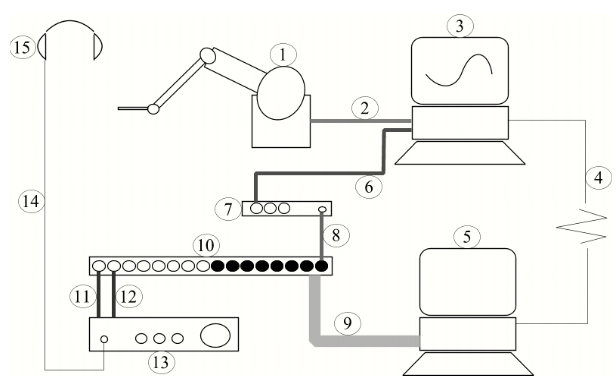

Figure 3. Set-up of our first sonified tactile line-graph

	Description
1	PHANToM Premium A haptic device
2	Connection to PCI card controlling haptic device
3	PC dedicated to virtual tactile environment
4	Ethernet Connection
5	PC with CP4 dedicated to 3D auditory environment
6	MIDI cable from PC MIDI OUT to synthesiser MIDI IN
7	MIDI synthesiser
8	XLR cable from synthesiser analogue output to rack patch
9	Connection from CP4 I/O module
10	19’’ 16 channel rack-mount patch panels
11	XLR cable to L input of amplifier
12	XLR cable to R input of amplifier
13	Denon audio amplifier PMA-535R
14	Headphone cable
15	HD 200 Sennheiser head phones

Table 1. Main elements of our development platform

The devices we are using provide us with as much control over the quality of the virtual environments as we need. Once we find out what works and what does not, we can optimise our design by making quality-functionality-cost tradeoffs. We have described our development platform in sufficient detail to enable its easy replication.

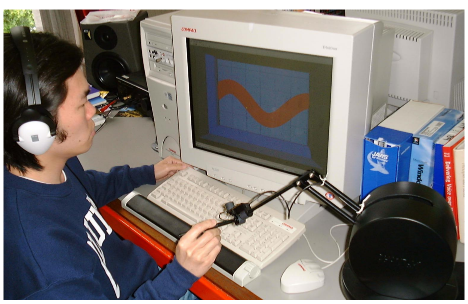

Figure 4. Exploring a line graph in the auditory and haptic media

SOUNDSCAPE DESIGN FOR LINE GRAPH REPRESENTATION

Here, our current sound mapping strategy for representing line graphs is described (Figure 5). We keep the design choice of mapping Y coordinates to pitch as there is enough evidence as mentioned earlier that this is an effective approach. Our enhancements include the creation of a sound source object, one for each curve, with varying pitch that can be positioned by the stylus of the haptic device. In addition, the listener/headphone object is fixed at the origin of the graph so that the ‘avatar’ of the user appears to be facing in the direction of the X-axis. Figure 6 shows the patch bay connections required to spatialise the sound source constituted of signals from the output of the synthesiser (Figure 3, item 7).

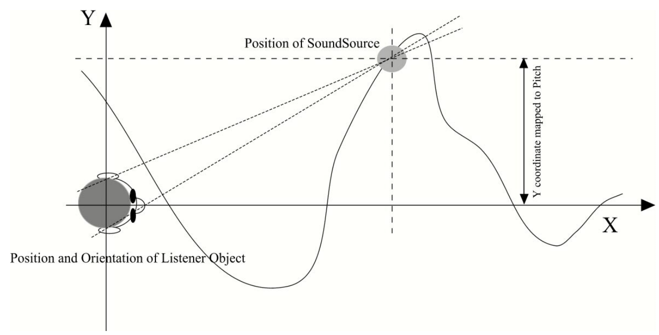

Figure 5. Sound mapping for our tactile line-graph

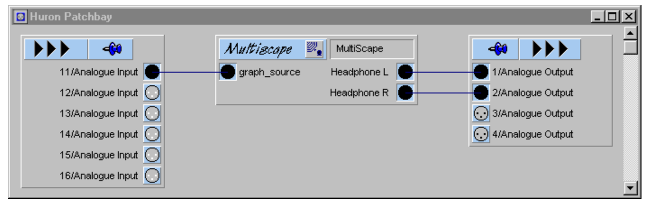

Figure 6. Patch bay connections for a line graph associated with a sound object

Our trials show that this choice allows the points of intersection of the curve with the X-axis to be detected immediately given that the jump of the source from the right to left or vice-versa is quite distinct. The intensity attenuation of the source with distance from the listener object also provides some cues for the current position of the stylus relative to the origin of the curve. We also introduce speech output to enhance the haptic display. The user is able to click for the exact x and y values of an x-y plot whenever such detailed information is required. The user is also provided the opportunity to key-press whenever an auditory overview of the curve is desired. This involves playing the appropriate pitches of the Y-coordinates in rapid succession to give a rough idea of the monotonicity or symmetry of the curve.

Integrating real world sounds with synthetic soundscapes

While the PHANToM haptic device is fairly quiet in operation, the introduction of spatial sound in our design can potentially disrupt existing channels of communication between classroom participants can be a source of annoyance to those for whom the auditory information may be redundant. In the type of classroom environment we deal with, it is likely that access to 3D sounds will be achieved through high quality headphones. While this prevents other students in the vicinity from being distracted, headphones have a tendency to isolate the listener so that the quality of peripheral real world sounds is reduced dramatically. This is an important issue that needs to be addressed before introducing any display involving spatial sound.

One of our attempts to address this problem involves the use of pre-amplified microphones that capture real world sounds before integrating the latter with synthetic sounds representing statistical information. The microphones used are two low impedance omni-directional electret condenser microphones with a reasonably large frequency response (50 to 50,000 Hz). One microphone is placed on each side of the subject's head using the arrangement shown in Figure 7.

Figure 7. Pre-amplified microphones for capturing real world sounds

The signals from each microphone are fed into the CP4 rack-mount patch panel (Figure 8) to create two omnidirectional sound sources (i.e left_mic and right_mic sources) within the virtual soundscape placed on both sides of the listener object. While this arrangement does mix real world 'binaural'(Brice 1997) sounds with synthetic sounds, we are finding it hard to fine-tune so that the whole auditory environment feels natural to the listener. We believe that continuous exposure to environments that do not 'feel' natural can lead to fatigue. Solutions which are potentially more successful include (1) the use of open earphones which are either open-back or have holes that allow environmental sounds to be heard while they are used, (2) the use of open earmolds which need to be fitted by an audiologist and which are designed to avoid masking environmental sounds.

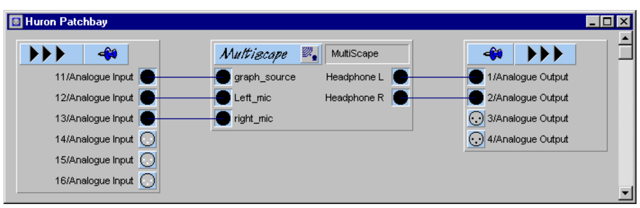

Figure 8. Patch bay connections for the integration of real world sounds in the information display

HAPTIC SURFACE DESIGN FOR LINE GRAPH REPRESENTATION

In this section, we describe our approach for designing virtual haptic environments for representing line graphs. We begin with an overview of haptic perception.

'Touch' Perception

Human touch receptors have been classified into two main categories: cutaneous and kinesthetic. The common notion of touch can therefore be considered to be composed of cutaneous and kinesthetic components that are needed to manipulate objects successfully and effectively, e.g. grasping a cup of coffee and turning the door handle. Cutaneous receptors reside beneath the surface of the skin and respond to temperature, pain and pressure. Kinesthetic receptors are located in muscles, tendons and joints, and correspond to the position of limbs and their movement in space (Klatzky and Lederman 1999). In visually impaired people, touch and hearing become their primary sources of sensory information. It has also been suggested that blind people develop increased sensitivity to information in these media (Kennedy, Gabias et al. 1992). For example, a pilot study shows that in a task involving the slope comparison of two lines in the haptic medium, the average number of errors by blind subjects tend to be less than that of their non-visually impaired counterparts (Yu, Ramloll et al. 2000). Further investigation is needed to determine whether the just noticeable difference in slope estimation for blind people is significantly lower than that of their non-visually impaired counterparts.

Tactile Displays

Braille, raised dots and lines have often been used in tactile graphs for visually impaired people who rely on the sensitive and rich cutaneous receptors of their fingers to explore the embossed details of a representative surface. A more recent class of kinesthetic displays are force feedback devices designed to provide a haptic channel of communication between humans and computers. They often take the form of electro-mechanical devices constraining motions in space in a variety of ways to produce compelling haptic sensations. In our case, holding a thimble or a stylus fixed to one end of some 'loaded' mechanical linkage, i.e. coupled with electrical actuators, allows a user to feel a reaction force which varies depending on factors such as the force applied by the user, physical properties of the virtual object touched and the position of the finger or stylus. While this approach simulates a single point contact with virtual objects accurately, it is a significant reduction in the haptic bandwidth when compared to the human's natural sensing ability in this medium. However, we believe that its functionality is sufficient for our purposes. Virtual objects can be manipulated, felt and weighed convincingly using such devices even if detailed and realistic texture rendering is difficult under single point of contact.

Haptic Surface Design for Line Graph Representation

Our pilot study involving three blind folded users and a blind user show that subtle changes to the design of the haptic surface can have significant effects on its effectiveness as a medium for data representation. This opinion is shared by an independent study which indicates that users found it difficult to track a virtual haptic graph represented by using a raised line (Figure 9), because of the natural tendency for the tip of the stylus to slip away from the surface of the raised object (Yu, Ramloll et al. 2000). This effect also contributed to difficulties in identifying endpoints of the line graph.

Trials with a slightly different design in which the raised line is replaced by a groove line look promising as users find it very intuitive to fall into the groove and to follow its path naturally (Figure 10).

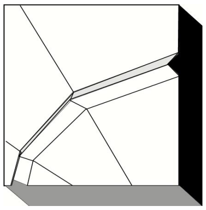

Figure 9. Raised surface design

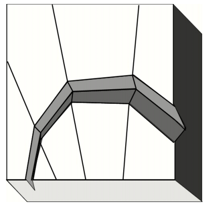

Figure 10. Groove design

Representing Multiple Curves on the Same Graph

Representing how multiple variables behave in relation to each other on a single graph is quite common and is an approach that strengthens the functionality of this analytic tool. However, this gives rise to a few design challenges in the haptic medium namely:

1. The differentiation of multiple curves on the same graph.
2. The resolution of tactile ambiguities at intersection points of the curves constituting the line graph (Figure 11).

Several curves or lines of a graph on the same surface can be confusing in the haptic medium if the surface properties or texture of the curves are not made easily distinguishable. This problem is exacerbated when line graphs intersect each other. In addition, they find the raised grid lines in the 'background', although designed to facilitate coordinate identification, can be a source of confusion (Yu, Ramloll et al. 2000). Therefore immediately distinguishable features are needed for the users to differentiate several curves or lines from each other.

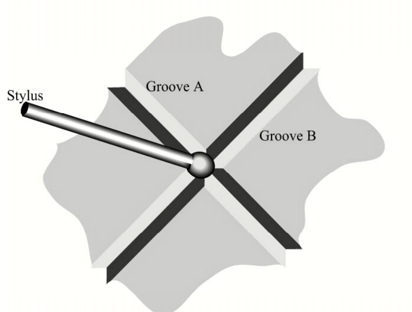

Figure 11. An ambiguous situation in a haptic only medium with uniform texture

One strategy to distinguish between multiple curves is to assign each with a distinguishing haptic characteristic. In a pilot experiment involving two curves with different friction characteristics, one feeling sticky and the other slippery, subjects failed to perceive the differences readily mainly because the raised surface made the tracing of the curve a difficult exercise. We hope that a groove design rather than a raised one will ensure that the stylus is constrained to move along the curves, thereby making it easier to focus on the distinguishing textures.

Recordings (Figure 12) of the position of the stylus during curve exploration tasks are rich in information about strategies adopted by users. For example, some users start with trying to identify the bounding square base containing the curves first, others try to explore the whole surface very quickly in order to have a rough overview before delving into the details. We also observed that the rendition of curves (Figure 13) are often less accurate than the recordings after an exploration task. In our opinion, this discrepancy is perhaps due to the fact that the rendition task is in itself a memory intensive task so that users may not recall the complete 'picture'. We have also observed instances where users deny to have felt a curve or parts of it even if the stylus position recordings show otherwise. These observations certainly warrant more investigation.

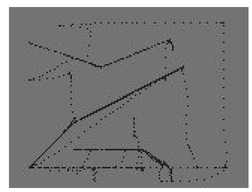

Figure 12. A typical stylus-position recording for a given exploration task

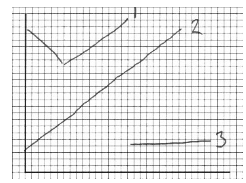

Figure 13. A rendition of the same curves associated with the figure 12 as perceived by a user

The single point contact constraint that our design faces makes a tactile overview of the graph difficult to achieve. We hope that the auditory overview will help to convey some general information about the tactile environment. However, we are still investigating ways of presenting the overview of the line graph in the haptic medium. A possible solution is to give the reader the opportunity to be guided automatically along salient aspects of the display, e.g. the borders of the display area, followed by the axes and then the curves. This strategy will hopefully allow the blind reader to construct a rough mental map or overview of the displayed environment. The blind reader is, of course, free to enter an interaction mode where he or she has full control of the stylus.

USER CONTROLLED v/s USER ASSISTED ACCESS

We feel that it is necessary to distinguish between the passive representation of line graphs and their active representation. The difference between the two types is that in the former the reader is a passive receptor of information while in the latter the reader is in control of the flow of information. We postulate that putting the reader in control of information access may have significant effects on the sustainability of reader-interest and arguably on the retention of the information accessed. This has been reiterated by information gained from (1) interviewing our prospective set of users and (2) think-aloud experiments performed on our early data visualisation prototypes discussed earlier.

An important requirement for our design therefore is that users should be given controlled access to auditory and tactile information. This means that they should be able to choose to have access to details of the information representation whenever they want to. However, there are also instances where they need to have assisted access to information. In the following we describe broadly our strategies to achieve these goals in the auditory and haptic environments.

Auditory environment

In our system, access to auditory information can be achieved in a number of ways. Provisions are made to allow the user (1) to position the listener object in the auditory environment (2) to change the x coordinate of the source object associated with a given line graph (3) to have access to detailed information in speech whenever required and (4) to have access to an auditory overview of the curve by playing the frequencies associated with the y-coordinates in rapid succession.

Haptic environment: A Case for Assisted Curve Tracking

The nature of the haptic representation ensures that the user has a reasonable degree of control on access to information. We propose the notion of assisted curve tracking which is characterised by a user being helped when following a curve. This may be viewed as a trade-off between full user controlled and full guided access to tactile information. For example, applying a force in the current direction of motion of a stylus along a curve will increase the speed in which the stylus is guided along a curve, applying an opposite force will slow it down and eventually cause it to pick up speed in the opposite direction. Applying no force on the stylus will ensure that it maintains its current speed in whatever direction it is moving along the groove. This strategy looks promising as a technique for dealing with the tactile ambiguities mentioned earlier. This is because the system has an accurate geometric model of the haptic surface so that from the system's perspective, points of intersection are not ambiguous. Thus the system can easily be made to guide a user along the path representing a given variable.

CONCLUSION AND FUTURE WORK

This paper describes our first steps in the design and implementation of sonified haptic line graphs for blind and visually impaired readers. Our participatory design approach has paid off in the early stages of the project given the wealth of requirements information gathered from our target user group. The next stage of our work will involve improving the current system so that it allows the user to construct and modify the sonified haptic line graphs in addition to browsing them. Line graphs are only one type of statistical information representation. The MultiVis project will investigate other techniques to convey statistical information such as scatter plots and tables. We are currently investigating ways of seamlessly introducing our solutions into the existing working environments of the prospective blind users. We also plan to construct a framework that describes various ways of integrating sound with haptics. There is a need to lay down guidelines that will enable designers to decide when a given medium should be used merely for feedback reinforcement, for primary information representation or even parallel information representation and to help predict the likely cross interactions betweens representations in haptic and auditory media. Finally, we believe that guidelines to design good tactile and auditory information representations, in the same spirit as existing guidelines in the area of data graphics (Tufte 1983), should be sought.

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REFERENCES

[1] Begault, D. R. and E. M. Wenzel (1991). Headphone Localization of Speech Stimuli. *Proceedings of the Human Factors Society 35th Annual Meeting*. **1:** 82-86.

[2] Brice, R. (1997). Multimedia and Virtual Reality Engineering, Newnes.

[3] Bulatov, V. l. and J. Gardner (1998). *Visualisation by People without Vision.* Workshop on Content Visualisation and Intermediate Representations, Montreal, CA.

[4] Gale, C. (1998). The Effects of Gaze Awareness on Dialogue in a Video-Based Collaborative Manipulative Task. *Proceedings of ACM CHI 98 Conference on Human Factors in Computing Systems (Summary).* **2:** 345-346.

[5] Gillepsie, A. (1997). Advanced Business Studies through Diagrams, Royal National Institute for the Blind, Archieve Ref. 551670/3, Royal National Institute for the Blind.

[6] Ishii, H. and M. Kobayashi (1992). ClearBoard: A Seamless Medium for Shared Drawing and Conversation with Eye Contact. *Proceedings of ACM CHI'92 Conference on Human Factors in Computing Systems:* 525-532.

[7] Kennedy, J. M., P. Gabias, et al. (1992). "Space, haptics and the blind." *Geoforum* **23**(2): 175-189.

[8] Kennel, A. R. (1996). AudioGraf: A Diagram-Reader for the Blind. *Second Annual ACM Conference on Assistive Technologies*: 51-56.

[9] Klatzky, R. L. and S. J. Lederman (1999). "Tactile perception with a rigid link from surface to skin." *Perception & Psychophysics* **61**(4): 591-607.

[10] Mansur, D. L. (1975). Graphs in Sound: A Numerical Data Analysis Method for the Blind. *Computing Science*. California, University of California, Davis.

[11] Poll, L. H. and B. H. Eggen (1996). Non-Visual Interaction with GUI Objects. *Proceedings of the HCI'96 Conference on People and Computers XI*: 159-168.

[12] Ramloll, R. (2000). Comparing workload for tabular data (30 rows x 10 columns) comprehension tasks under 'speech only condition' with 'speech and pitch condition'. Glasgow, GIST, Department of Computing Science, Glasgow University:

[13] Internal Report available at http://www.dcs.gla.ac.uk/~rayu/publications.shtml.

[14] Ramstein, C., O. Martial, et al. (1996). Touching and Hearing GUI's: Design Issues for the PC-Access System. *Second Annual ACM Conference on Assistive Tech-nologies*: 2-9.

[15] Sahyun, S. and J. A. Gardner (1998). Audio and Haptic Access to Math and Science - Audio graphs, Triangle, MathPlus Toolbox, and the Tiger printer. 15th IFIP World Computer Congress, Vienna.

[16] Tufte, E. R. (1983). *The Visual Display of Quantitative Information.* Cheshire, CT, Graphics Press.

[17] Yu, W., R. Ramloll, et al. (2000). *Haptic Graphs for Blind Computer Users*. Haptic Human-Computer Interaction Workshop, Glasgow University.