Graph Builder: Constructing Non-visual Visualizations

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This paper introduces a novel application called Graph Builder, which allows visually impaired people to interactively construct bar graphs using a force feedback device. We discuss the limitations of current technology to allow such interactive construction and explain why, in educational environments, such interactive construction is important. Evaluations of Graph Builder showed that users could construct graphs accurately. However results showed that a large number of 'off-by-one' errors occurred, where the bar was set either one unit too high or too low. Revisions to the mechanism to manipulate bars were made, and further non-speech audio feedback was added. A further evaluation showing that the proportion of 'off-by-one' errors had been reduced.

Keywords: haptics, visual impairment, non-speech audio, graph construction.

1 Introduction

There are currently 11.4 million visually impaired people in the United States [Ross & Blasch 2002] and 2 million in the United Kingdom (http://www.rnib.org). Many of these users interact with computer systems using screen reading software such as JAWS (http://www.freedomscientific.com). This technology, whilst allowing access to textual data, is less good at providing access to graphical data such as the graphs, charts and tables that sighted people use in their everyday lives. Alternative technologies to access such information are available, but these involve creating raised paper diagrams from computer printouts. These diagrams are inflexible as they cannot be altered after production, and the user is unlikely to be able to inspect the diagram until it is produced on raised paper. Lack of easy access to this information is a major obstacle to blind and visually impaired people who are pursuing scientific study and careers [Dimigen et al. 1993]. There are additional problems where graphs and diagrams must be hand-prepared by students, such as in mathematics classes, where automatic generation via a spreadsheet program would not be sufficient for a student to show understanding of the graphs. Currently available technologies make it difficult to initially create graphs as well as change them after creation. Since learning to construct graphs involves making mistakes, understanding those mistakes and revising the graph interactively [Clamp 1997], solutions to allow students to learn effectively are required. There has been little research to provide access to diagrammatic representations such as graphs. Almost no work has been carried out to provide visually impaired users with the ability to interactively construct graphs. Current non-computer based techniques available to construct visualizations have several issues such as the inability to make changes and retain the graphs that are produced. All are unsuitable for communicating data outside an educational environment.

This paper discusses the design and evaluation of a haptic computer based application that allows visually impaired people to interactively construct mathematical graphs; allowing those graphs to be permanently retained, browsed and modified. We start by presenting requirements capture work which highlights the problems of currently available techniques for graph construction, before discussing our novel application called Graph Builder and its evaluation.

2 Background and Motivation

In order to determine the issues involved in graph construction for visually impaired people, a group discussion and interviews were held with visually impaired students at the Royal National College for the Blind (RNCB) in Hereford, and classroom observations were held at the Royal Blind School (RBS) in Edinburgh. At the RNCB, a vocational college in the south of England, a group discussion with six participants and two individual interviews were held. All of the participants were between the ages of 18–24 and were visually impaired when taught graphs at school. Participants studied a range of subjects (such as music technology and English literature), and all used a computer regularly for communication (such as email and Web browsing). Participants were all asked about their experiences of using and constructing graphs. In all cases participants were asked to introduce themselves, before the experimenter posed each of the following questions for discussion.

- In what ways do you use graphs and tables in your everyday lives?
- What sort of tools and technologies do you use to access graphs, and what are your views on them?
- What are your experiences in creating graphs?
- What sort of difficulties do you have when answering questions using graphs?

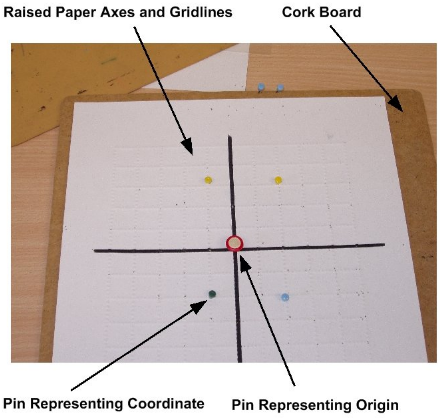

Figure 1: An example of the materials used when constructing a graph using the corkboard technique.

Participants were asked to discuss their views on the questions freely. The interviews and group discussion were recorded to allow for later transcription. Each interview lasted approximately 30 minutes with the group discussion taking around an hour. All participants were paid £5 for taking part.

At the RBS two teaching sessions were observed. Each session involved one-on-one teaching between a student and teacher on graph understanding and construction. Both students were between 16 and 18 years old. The experimenter quietly observed as much as possible during the lesson but did on occasion ask the student and teacher questions when relevant. One student was studying Standard Grade mathematics. In this lesson the teacher used a cork board and pins (see Figure 1) to demonstrate simple graph construction to the student, who also demonstrated constructing some graphs for the teacher. The second student was partially sighted and was studying Higher Grade mathematics. She was being taught how to transpose graphs along an axis, with the aid of both raised paper diagrams as well as a page magnifier. No parties at the RBS were paid for involvement in this study.

The most common technique used in schools for visually impaired people to construct graphs is to use a corkboard covered with a raised (swell) paper overlay presenting grid lines. Pins are pushed into the cork, and rubber bands wrapped around the pins to form the components of the graph such as bars, lines, etc. See Figure 1 for an example. This technique, whilst being cheap and simple, has a number of issues. Firstly, the pins used can fall out if not pushed in far enough, causing the student's hard work to become lost. Additionally the rubber bands used can easily fall off the graphs if a pin falls out, or if a pin is removed if the graph needs to be modified (e.g. a bar in a bar graph is set to the wrong value). Since the pins used are sharp so they can be driven into the board, care must be taken to ensure students do not injure themselves. Several participants in the group discussion noted that they had hurt themselves when using such a technique. One final issue is that the graphs created by students are rarely retained after they have been constructed. The graphs must be dismantled so that the equipment can be reused. Several participants in the group discussion found that this was 'a bit disheartening'.

An alternative technique for graph construction is to use a Braille typewriter. Participants in the group discussion noted that this was only useful for bar graphs with a limited number of bars. This technique allows for a permanent record of the graph to be kept, however the entire graph must be redrawn from scratch if a mistake is made. This is problematic since it is the interactive construction, making mistakes, understanding and correcting those mistakes that allow a solid understanding of graph concepts to be built up [Clamp 1997].

An additional problem with all of the techniques mentioned is one of speed. Participants found graph construction to be slow and cumbersome to a detrimental degree on their education. One participant saying:

> 'in my maths exams, if there was ever a question asking me to draw a graph for a set of figures, then I'd just miss it out and go onto the next one. I thought I might as well not even bother trying, it's so time consuming … I wasn't going to sit there for three-quarters of an hour doing a little graph.'

Clearly any computer based solution must allow graphs to be constructed quickly, with minimum overhead caused by the technology used.

From the observations, group discussion and interviews we can conclude that all current techniques to construct graphs have issues. They are either non-permanent and cannot be retained, or are so permanent that they cannot be modified if a mistake is made. In all cases they are time consuming and 'fiddly'. Our solution overcomes these problems, allowing graphs to be constructed and modified with ease in a timely manner.

3 Computer-based Graph Access

Whilst only one study has investigated interactive construction of graphs, work has been undertaken to provide computer based access for visually impaired people to browse graphs and other mathematical diagrams.

Fritz & Barner [1999] have constructed a haptic-based system, using a PHANTOM haptic device from SensAble Technologies (http://www.sensable.com), that allows a user to explore the plot of a three dimensional function. Unfortunately they do not present an evaluation of their work. Yu & Brewster [2003] have designed and evaluated a PHANTOM based system to allow visually impaired users to browse simple line and bar charts. They have successfully shown that visually impaired users can extract information on the trend of a graph as well as being able to answer more detailed questions about the information contained within it. They also identified that adding non-speech sound to the haptic environment was an effective way to improve performance. They produced a set of guidelines which we have used to construct the novel tool discussed here.

In addition to the studies using haptic systems to allow visually impaired people to browse graphs, there have also been audio based solutions which have provided effective access to mathematical graphs. Mansur's [1985] SoundGraphs pioneered the technique of using pitch to represent the *y*-axis of a line graph and time to represent the *x*-axis. The use of such line graphs has been heavily studied, and have been found to effectively communicate trend information to users [Brown & Brewster 2003]. Unfortunately, only limited work has been undertaken to identify how other forms of diagram such as pie and bar charts can be sonified to be presented to users [Franklin & Roberts 2003].

The work discussed above shows that using haptics and non-speech sound is an effective way to present diagrammatic based mathematical data to users who are visually impaired. It is therefore a logical step to use such technology to build an interactive graph construction tool. Before discussing the design of our tool however, it is necessary to consider the limited work that has been undertaken on haptic and audio based graph construction applications.

There has been little work investigating graph construction for visually impaired people. Yu et al. [2003] have built a simple system using a Logitech Wingman force feedback mouse that allowed users to key in values for a graph and have the graph haptically rendered so that it could be felt with the mouse. The system is similar to the graph plotting system of Microsoft Excel and does not allow interactive manipulation, which as previously discussed is important in an educational environment. An evaluation showed that users could create and browse graphs, and that a combined haptic and audio interface produced lower errors than a solely haptic interface. However due to difficulties in accessing enough visually impaired people, they performed their evaluation on blindfolded sighted people. Yu et al. [2003] also developed an interactive graph building tool for line graphs using the Wingman mouse. Users set consecutive points on a line graph by clicking a haptic grid with the mouse. Their system did not however allow for points to be modified after being set, so users would have the same problems as using a Braille typewriter. If a mistake was made, the user would have to start the graph again from scratch, unlike a sighted user who may just remove the incorrect point on a paper based graph using an eraser and redraw the line. The system discussed in this paper overcomes such issues, allowing graphs to be dynamically altered with ease. Again Yu et al. performed no formal evaluation with visually impaired users, blindfolded participants being used instead. Van Scoy et al. [2001] have constructed a tool that will read and parse a mathematical expression, and produce a virtual haptic representation 'carved' into a virtual surface that can be explored using a PHANTOM haptic device. Unfortunately they do not report an evaluation of their system.

Using an automatic tool to construct a graph, whilst being useful to show the shape of a function, etc., assumes that the student understands the graph type created. This is useful when studying mathematics at say university level, but not when the concept of graphs is being introduced for the first time. As with other subjects simply being told something does not show understanding of it. As already mentioned, it is the interactive construction, making mistakes, understanding and correcting those mistakes that allow a solid understanding of graphs to be built up [Clamp 1997].

Supporting these tasks is a feature that all of the tools discussed above, and the technologies currently used in the classroom fail to do. In the next section we will introduce a novel application which takes account of these issues, as well as

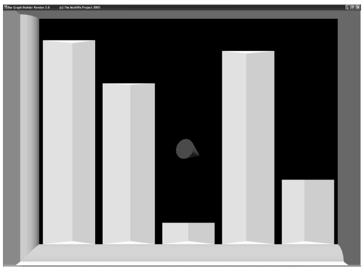

Figure 2: A screenshot of the Graph Builder application showing the recessed 'V' shaped bars. The current position of the PHANTOM in the graph (and thus that of the user) is represented by the cone shaped object. The colours used are of high contrast to aid those with residual sight.

Figure 3: A picture of a SensAble Technologies' PHANTOM Omni haptic device as used in the Graph Builder application. The user interacts with the 'pen' which also contains two buttons for interaction.

overcoming the problems of current graph building techniques as identified at the RNCB and RBS, to allow users to interactively construct simple bar graphs.

4 Application Design

Since, as already stated, there is little research into interactive applications to construct graphs, the approach adopted here was to build an application using guidelines derived from prior work on haptic graph browsing. Our application was based on the guidelines described and evaluated by Yu & Brewster [2003]. A screenshot is shown in Figure 2. The application was constructed using SensAble Technologies' OpenHaptics API. The user could feel the graph by using a PHANTOM Omni force feedback device (see Figure 3) which uses motors to resist user movement providing the impression of a physical object.

The graph is built as a 2.5D object presented on a vertical plane in front of the user, with recessed 'V' shaped grooves to represent each bar. These being easier to follow with a single point of contact haptic device than the raised lines found on swell paper graphs [Yu & Brewster 2003]. The axes were represented as raised cylinders so they provided a contrast to the recessed bars. The background was textured to differentiate it from the rest of the graph, and the entire graph was contained within a box to ensure that a user could not 'lose' the graph. Additionally the colours used for graph features are of high contrast to aid users with residual sight. However since it is difficult to quantify residual sight, participants is all the following evaluations were not allowed to look at the screen. Users could request the names of the *x*- and *y*- axes, the title and the names of individual bars in the graph by touching the appropriate feature and pressing one of the two buttons on the PHANTOM pen. For example, touching the *x*-axis and pressing the button would cause the name of the axis to be spoken using synthetic speech. Our approach allows users to concentrate on the logical units of the graph such as bars, axes, etc., rather than worrying about the smaller details, such as making sure all of the bars are the same width. Additionally, the complexity of the task can be altered. In the evaluations of the application discussed here, users were only asked to set the scale, axes titles and the values of the bars. However, there is no reason why users should not be able to add and remove bars and axes, dependant on the particular feature of the graph a teacher wishes to concentrate upon teaching. Graph Builder makes such scalability possible. Additionally, the application allows the graph to be saved, manipulated and printed at any future date overcoming the limitations of other technologies previously discussed.

With Graph Builder, users can modify the graph by sliding the bars up and down. Users select a bar by touching the top of a bar and holding down the second of the two buttons on the PHANTOM pen. A small gravity effect is then applied to make the bar feel 'weighty', and the user is constrained to moving the PHANTOM pen in a vertical direction only. As the user moves the pen up or down the value of the bar is changed. In order to provide the accurate detail required when constructing a graph, non-speech audio cues have been added to provide specific information about the value of the bar whilst is being moved.

As the user drags the bar being modified over each unit on the *y*-axis a different MIDI note is played, giving the user information about the current value of the bar. As such, one note is played for each unit increase or decrease in bar position. Using different notes should ensure that participants do not become confused over the direction of movement. Counting the number of notes played also provides information about the value of the bar. Using speech to read out the values of the bars was considered but was felt to be unsuitable for an educational environment where the emphasis is on the ability of students to show their understanding of graphs, rather than just get the answer from the application.

5 Initial Evaluation

When evaluating systems for the visually impaired it is commonly difficult to recruit enough participants to perform large scale empirical evaluations. Because of this many researchers choose to initially test and refine their design with blindfolded sighted users, only testing on visually impaired users when a refined system has been developed. This technique works well when there is a developed body of work supporting the underlying application. However, due to the lack of previous work

Food	Calories per Gram
Cheese Curls	12
Mixed Fruits	14
Vegetable Soup	2
Butterscotch Bar	21
Chocolate Chip Cookie	10
Carrot Muffin	17

Table 1: An example table for the graph drawing question: 'Construct a bar graph showing the calories in each of the following foods'.

on graph construction we cannot be sure that underlying assumptions in our design lead to a system which will be usable by visually impaired people. Rather than spending time and effort to create and refine a system only to find out that it was 'wide of the mark' when finally evaluated with visually impaired people, we decided to perform initial evaluations on visually impaired people. If the basic technique is successful, refinements to the design can be evaluated with blindfolded sighted users and ultimately validated with local visually impaired 'expert' users.

5.1 Evaluation Design

The evaluation was a mixed Think Aloud and empirical study, and was performed at the RNCB, Hereford. There were four participants all between the ages of 18–30; all had become blind before they had initially studied graph construction at school. Each participant was paid £5 for participating in the study. Participants who had good domain knowledge of graph construction were chosen since Pinker [1990] notes that such knowledge is one of the key factors in an individual's ability to construct graphs, and we wanted to ensure that a lack of such knowledge did not appear in the results as poor design of the application.

Participants completed a total of 5 graphs each. The first graph was used as a training session where the experimenter helped the participant, ensuring that they had a good understanding of the tool and how it worked. For each graph, participants were given a table and asked to construct a graph from the data in the table (see Table 1 for an example). The table and question were read aloud by the experimenter and could be repeated whenever requested by the participant. All of the questions were based on those found in the General level Standard Grade syllabus [Brown et al. 2004], which is the standard Scottish qualification taken by students in the 14–16 age range. To answer the question participants initially had to decide on the name of the graph, x-axis, y-axis and a scale (how many units of data would be represented by one unit of the y-axis).

This information was requested from the participants, and since the application was not yet integrated with screen reading software, entered into a dialogue box by the experimenter. Participants were then instructed to complete building the graph and notify the experimenter, who could monitor their progress on the computer screen, when they had completed the graph. Participants were encouraged to

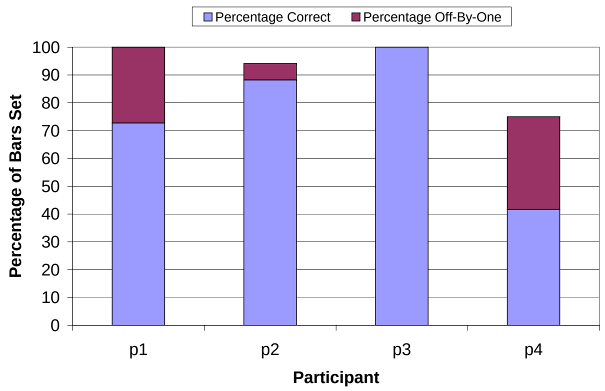

Figure 4: Graph showing the total percentage of bars correctly set by each participant, and the percentage of 'off-by-one' errors, where the bar was set either one unit too high or one unit too low.

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talk about what they were thinking and doing during the experiment, and relevant points were noted by the experimenter to be discussed during the interview phase. After completing the graphs, participants were informally interviewed about their experiences in using the application, as well as specific problems that had been noticed during the tasks. Interviews were recorded for later transcription. Overall each participant took around an hour to complete the experiment.

5.2 Graph Building Accuracy

For each graph completed, one mark was awarded for appropriate values for each of the *x*-axis, *y*-axis, graph title and *y*-axis scale. A mark was also awarded for each correctly set bar in the graph. All participants scored full marks for the titles of the graph, the *x*- and *y*-axes titles, as well as the scale for the *y*-axis. Figure 4 shows the percentage of correctly set bars for each participant over the course of the experiment.

The results show that participants can construct bar graphs successfully using Graph Builder, with three participants setting over 70% of bars correctly. However, there are a large proportion of off-by-one errors (68% of all errors) where a bar was set either one unit too high or one unit too low. For example, a bar which should be set at 10 was set at 9 or 11. During the informal interviews with participants, reasons as to the large number of off-by-one errors became clear. These reasons are discussed in the following section.

5.3 Participant Comments on Graph Builder

Overall participant views of the application were positive, and all considered that the concept was superior to existing tools they had used in school. Participants were also positive about the logical construction system, where graph objects are provided and modified rather than users having to ensure that all graph bars are the same width, etc. Participants felt that this allowed them to concentrate on the important features of graph construction. As one participant noted 'it takes a lot of the 'leg work' out of graph drawing'. There were however several common usability problems identified.

Firstly, participants found the method used to select and move the bars problematic and this may have caused some of the off-by-one errors. When selecting the bars, participants found that it was difficult to press the pen in an upwards direction (to keep it against the top of the bar) and then press the button (providing a downward force) without moving the PHANTOM away from the top of the bar and thus not selecting it. Participants tended to use more force than necessary when holding the pen against the top of the bar. When the bar was selected, the upwardly applied force was much greater than the downward gravity effect applied to make the bar feel 'weighty', causing the bar to jump one or two positions before the user stopped the PHANTOM pen moving. Another issue may have occurred when the button was depressed (to set the value of the bar). If the current position was at the borderline of one value and the value above or below it and the PHANTOM pen was moved slightly when depressing the button, an incorrect value may be set and again an off-by-one error occurred. It seems from participant comments that using buttons on the pen of the PHANTOM was not a useful way to modify the graph.

Another issue raised was not being able to determine the actual value of a bar after it had been set. Whilst different MIDI notes were played to provide information about the current value when modifying the bar, it was not possible to precisely determine the bar value at a later point. If the user felt that a mistake had been made, the only option available was to move the bar to zero and then move it back to the correct value. We had considered that using different notes for each *y*-axis position would allow participants to determine if the value had been correctly placed, but this was not the case. It is likely that these two problems combined to produce the relatively high proportion of 'off-by-one' errors found in the results (68% of total errors were off-by-one errors). See Figure 4. Solving these problems therefore should increase the ability of users to successful produce graphs with the Graph Builder tool.

A final problem was identified when requesting information about features in the graph. As already stated, touching either the axes, or any of the bars, and pressing a button on the PHANTOM pen caused the name of the axis or bar to be read out using synthetic speech. Conversely the background of the graph and the box that constrained the graph provided no information when touched by the PHANTOM. Several participants found this distressing and despite having these features explained to them before the experiment, claimed that the application had broken and 'wasn't working' when it did not respond to requests for information from the background and constraining box. This is an important point since for this user group, as when an application fails to produce sound output it is an indication that the program has crashed. The application should therefore produce sound output for all of the features that a user can touch in the environment.

6 Graph Builder Revisions

The initial evaluation of Graph Builder showed that visually impaired users could effectively manipulate and modify graphs with a high degree of accuracy. However, due to the points raised, several modifications were needed.

The ability of participants to select bars was the major criticism in the initial evaluation. Using the buttons located on the pen as well as the mechanism used to select and lock onto bars proved problematic; as did the inability to review the value of the bar after it had been set. In order to overcome these problems the button used to select bars was changed, with the 'Ins' key (the 0 key) on a standard numeric keypad used instead of the PHANTOM button. The 'Ins' key was chosen since it is a uniquely shaped key on a keyboard and should therefore be easier to find. Using this key means that there is no movement in the pen due to pressing the button to select a bar. Additionally rather than the problematic mechanism of firstly touching the top of the bar with the pen before pressing the button, holding down the 'Ins' key effectively changes the mode from browsing to modifying. With the revised system, as soon as the user touches the top of the bar whilst holding down the 'Ins' key, the bar becomes selected automatically and can be manipulated in the same way as the original version of Graph Builder. Releasing the 'Ins' key changes the mode back to browsing and causes the bar to be set at the current position. Using this method it should be easier to hold the pen steady when setting the bar and avoid the problems that occurred in the original system. In order to make it clear that the user had 'locked onto' a bar, a 'clunk' sound was played when the user successfully selected a bar, the same sound was used when the user set the bar position by releasing the 'Ins' key.

To provide the ability to determine the value of a bar at a later time, the button on the PHANTOM pen which had been used to modify the graph was used to present the value of the bar. Touching the bar and pressing the PHANTOM pen's button caused the value of the bar to be presented. Presenting the value of the bar in speech was considered, however since a potential application of this system is in the classroom, we felt that presenting speech would not be appropriate. Providing speech may be simply providing the answer, rather than requiring the student to work it out for themselves[1]. Instead of speech, the sequence of the notes played when modifying a bar was used. Therefore, if the bar value was ten (and the graph scale set at one), ten notes were consecutively presented at approximately half second intervals. This is analogous to a user with a visual graph counting along the *y*-axis to find the height of a bar. This sequence of notes could be played on demand by the user, and was also played when the user set the value of a bar by releasing the 'Ins' key, allowing immediate review of the bar value.

Concerns by participants of the system having crashed when it did not 'talk to them' were solved by making all of the objects in the graph provide some speech feedback when they were touched and the PHANTOM button was pressed. Navigation feedback was provided, as Challis & Edwards [2001] note that large amounts of dead space (where no useful information is contained) can cause confusion to a visually impaired person. They recommend that no such space exists in tactile diagrams for the visually impaired, but since it is not possible to remove such space from graphs, having that space providing navigational cues is the next best option. For example, the background of the graph provided the information 'move down to get to a bar'. This should reduce the likelihood that participants feel that the application has crashed because it does not provide audio feedback.

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[1] Later informal discussions with a teacher of visually impaired students indicated that this is partially correct, and it would be better to have both speech and non-speech available as an option.

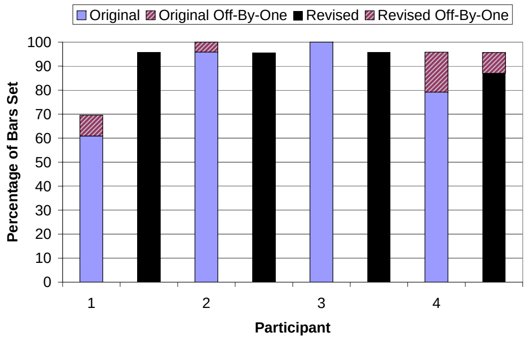

Figure 5: Graph showing the total percentage of bars correctly set for each participant for the original and revised Graph Builder applications, and the percentage of 'off-by-one' errors.

7 Evaluation of the Revised Version

As already stated, a common problem when evaluating applications for visually impaired people is obtaining access to a sufficient number. Whilst the original evaluation used visually impaired people to test Graph Builder, this was due to the novelty of the system, with little prior work indicating its usefulness. Since the first evaluation showed that users could understand and manipulate graphs, the revisions were evaluated with normally sighted, but blindfolded participants.

Four participants between the ages of 18–24 carried out the experiment, which was of a within groups design. All participants were students at the computing science department of Glasgow University, and were familiar with graphs. This is important for the same reasons outlined in the previous study where domain knowledge may have an impact [Pinker 1990]. Participants completed questions similar to the one shown in Table 1 with the initial Graph Builder system (the 'original' system) and the revised Graph Builder system (the 'revised' system). The order in which participants undertook the conditions was counterbalanced. Two sets of questions with similar difficulty were used, with the sets being counterbalanced between the conditions. The graphs produced by participants were scored using the same method as the original evaluation. The results are presented in graphical form in Figure 5 and show that there is little difference between the two conditions. Both conditions produced highly accurate graphs. Notably however, the proportion of 'off-by-one' errors which were prevalent in the original Graph Builder (46% of all errors) were reduced in the revised version (33% of all errors). In comparison to the results of the original evaluation at RNCB, the blindfolded participants had a lower proportion of off-by-one errors with the original system (46% of total errors (7% of total bars set)) than the visually impaired people at RNCB (68% of total errors (16% of total bars set)). This may be down to several reasons. For example, many visually impaired people do not use a pen often which may have contributed to problems when using the pen like interface on the PHANTOM. This indicates that more substantial reductions in off-by-one errors would result if the revised version was tested with the visually impaired participants from the original study.

Whilst there seems to be little quantitative difference between the two conditions in terms of the bars that were correctly set, informal comments by participants expressed preference for several features incorporated in the revised version of Graph Builder. Notably participants liked the ability to review the value of the bar after it had been set, as well as having sounds to indicate that a bar had been selected. Participants said that the addition of such features gave them 'more confidence' that the correct value had been set. However they disliked the value of the bar being replayed immediately after it had been set, finding it annoying, and would like that feature to be optional.

8 Expert Evaluations

The results of the previous experiment are encouraging. In both conditions participants were able to accurately construct graphs, with the number of off-by-one errors being reduced with the revised Graph Builder application. Additionally informal participant comments indicated preference for the revised version. In order to confirm the usefulness of the revised Graph Builder, a further evaluation was carried out using two locally available 'expert users'.

Both participants were between 30–50 years old, were visually impaired and had extensive experience of computer based access technologies for visually impaired people. Both had good domain knowledge of graphs. One participant was an academic researcher at a British university, whilst the other was a transcription officer for the RNIB (Royal National Institute for the Blind). Both had limited experience using the PHANTOM haptic device, and neither had previous experience with Graph Builder.

The evaluation consisted of each user performing two to three questions with each of the Graph Builder systems whilst being asked to talk about what they were doing in a Think Aloud style. After using each system they were asked for their overall comments on it. After both systems had been used, the experimenter discussed participants' comments on both systems and had a general discussion about the previous evaluation studies and what had been discovered. Participants' comments were recorded for later transcription. Overall both participants were able to construct graphs with both systems to a high degree of accuracy.

For the original version of Graph Builder, the main comment that was raised was the inability to review the value of a bar after it had been set. Both participants mentioned that although they felt that the bars had been correctly set, they were not confident in that opinion. One user said that:

> 'if I had been sitting an exam I would have set and reset that bar a dozen times to make sure I had it set correctly.'

These views are consistent with the views expressed in the two previous experiments. For the revised version, both participants suggested that playing the value of a bar immediately after it had been set should be an option and it should be possible to switch off playing the sounds immediately if desired. Again this view is consistent with the results from the blindfolded sighted study.

The first participant also discussed some more problems counting the number of units moved when manipulating a bar. He noted that if the bar was moved quickly, or jerkily, it was easy to lose count of the position of the bar. He noted that this problem was more prevalent in the original Graph Builder where bars were selected by using buttons on the PHANTOM pen rather than by changing modes using a keyboard key, as was done in the revised Graph Builder. This is consistent with the bar selection issues identified in the initial study with the 'original' Graph Builder at RNCB, and provides conformation of the usefulness of the revised mechanism to manipulate the bars.

9 Guidelines

From the work carried out in this paper we can identify the following guidelines to assist future designers of haptic applications for the visually impaired.

All touchable objects should provide audio feedback. Participants using the original version of graph builder complained that the application had 'crashed' when attempting to gain audio feedback about the graph background, even though they were aware that only the axes and bars provided audio feedback. If any feature of the environment provides audio feedback, then all features should provide audio feedback. As was the case with Graph Builder, although participants may be able to feel the object, they may still feel the application is not working if audio feedback is not provided.

Use caution when requiring selection of objects. The major problem with the initial version of Graph Builder was selecting and manipulating bars due to using the buttons on the PHANTOM pen. Changing to keys on the keyboard was preferred by participants. Since it is possible to inadvertently manipulate the object when selecting it (as the users did when selecting the bars in Graph Builder), it may be better to ensure the selection control is physically separate from the manipulation control. Requesting information via the same control (such as bar names and values) however, is possible.

10 Conclusions

For students to be able to understand graphs it is important that they are able to construct them. Understanding of concepts comes from trying to carry out tasks and making, understanding and correcting mistakes [Clamp 1997]. This requires students to be able to construct graphs and easily manipulate them when mistakes are made. Requirements capture with visually impaired student showed that techniques currently used in the classroom are either so permanent (such as using a Braille typewriter) that they could not be easily manipulated or changed, or could only be changed at considerable cost (such as using a cork board). Additionally, the degree of inflexibility of the techniques used makes the process of constructing graphs slow, causing students to avoid constructing graphs in exams and as such scoring a lower mark than if better tools for construction were available. The application introduced in this paper, Graph Builder, overcomes many of these problems, allowing users to interactively manipulate the bars, without the possibility of bars changing by themselves as might occur if a pin were to become dislodged when using the cork board technique. As such Graph Builder provides the permanency of the Braille typewriter technique, allowing graphs to be kept permanently, whilst providing the ability to change and manipulate those graphs as with the corkboard technique. Additionally the 'fiddly' elements of graph construction have been removed. Whilst one participant estimated that it took 45mins to complete a graph in an exam using existing techniques, participants were able to construct 5 graphs in an hour using Graph Builder. Whilst, not all features of graph construction were investigated through this study (participants did not have to draw axes, etc.), the study does indicate that the time taken to construct graphs could be significantly reduced if Graph Builder is expanded to provide effective mechanisms for the currently unsupported features.

Whilst we can consider Graph Builder to be useful for the creation of graphs, we have yet to evaluate its use in a classroom environment. Future studies must consider the impact of Graph Builder in such an environment with students who are learning how to construct graphs, and do not have the good domain knowledge, that the participants in our studies had. Such future development of the Graph Builder application will allow technologies to be deployed which will significantly assist visually impaired peoples' learning and understanding of graphs.

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