A Study of Blind Drawing Practice: Creating Graphical Information Without the Visual Channel

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ABSTRACT

Existing drawing tools for blind users give inadequate contextual feedback on the state of the drawing, leaving blind users unable to comprehend and successfully produce graphical information. We have investigated a tactile method of drawing used by blind users that mimics drawing with a pencil and a paper. Our study revealed a set of properties that must be incorporated into drawing tools for blind users, including giving feedback for relocating important points, determining angles, and communicating the overall structure of the drawing. We describe a grid-based model that provides these properties in a primitive-based 2D graphics environment, and we introduce its use in drawing and other graphical interactions.

KEYWORDS

Non-visual drawing tools, GUIs for blind users, contextual inquiry, feedback, grid

INTRODUCTION

When sighted persons draw, they continually adjust their input based on visual feedback from the image that they are drawing. This process is essential for capturing a user's mental model of the real world on a graphical medium. Current drawing tools designed for blind users miss this element of feedback-based input.

For this reason, we have explored applying a method already intuitive for blind users to design a tightly coupled input/output model. This model supports a set of properties that can be applied to the design of any drawing tool (e.g., tactile, non-speech, and speech-based drawing tools).

An effective electronic drawing tool for blind users will open up communication between the sighted and the blind to the rich medium of graphical information. Such a tool would also offer a method for studying blind users' mental models of the world.

The predominant user interface paradigm dramatically affects blind computer users. During the era of the command-line interface, blind users used computers as effectively as sighted users, because both groups could efficiently use keyboards for input, and output was confined to a well-defined grid of characters.

The advent of graphical user interfaces (GUIs) changed the way users interact with computers; accessing information became more intuitive for sighted users but much harder for blind users. By 1990, activists in the blind community brought attention to the crisis created by the inability of screen reader technology[1] to adapt to the new GUIs created by the sighted community [4]. This crisis illustrates two important points. First, changing the method of input alters a user's access to information. Second, blind users have been forced to imperfectly adapt their own abilities to new methods of accessing information, rather than having tools that are adapted to their special needs.

In general, software applications are designed with sighted users in mind, requiring users without this ability to adapt [7, 9]. They depend on sophisticated GUIs using direct manipulation techniques, which leave vision-impaired users without feedback they can understand. Drawing programs are a good example.

One of the major problems with using a drawing program arises when visually impaired persons attempt to use the cursor to find their way back to a previously selected point on the screen. This problem is as challenging as having a sighted person use a computer with the monitor turned off. Blind users have had only limited success in using drawing programs because traditional drawing software lacks the capability to translate graphical data output in a way that screen access programs can interpret.

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[1] A screen reader or screen access program captures text data sent to the screen and reroutes it to a voice synthesizer to provide audio voice feedback.
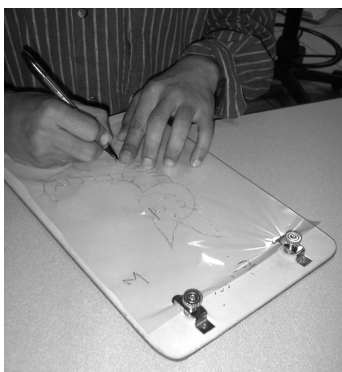
Figure 1. Drawing using a tactile graphics tablet.

Millar showed the importance of visual feedback in a study comparing the ability of congenitally blind and sighted but blindfolded children to draw the human figure [13]. Millar found that visual feedback was important for level of detail, articulation of the drawing, and for cohesion and alignment of the parts. Sighted but blindfolded children performed only slightly better than congenitally blind children in creating details, cohesion, and alignment.

To understand what types of feedback a drawing program must include, we looked at a tactile method of drawing used by blind users that mimics drawing with a pencil and a paper (see Figure 1). We conducted a study in which five participants were given four tactile freehand drawing tasks that were intended to explore the effectiveness of this method and the features that would be required in other drawing tools. Our study, described below, revealed that a drawing program should support several important properties, both for blind and sighted users. When drawing, one of the most important operations is to be able to locate and relocate important points. Sighted users take this operation for granted. A blind user must also be able to conceptually relate one point to the whole image or another point in the image. Some guideline or frame of reference is needed. This same frame of reference must also offer a mechanism to specify the angle of a line being drawn or to describe the angle of a line being accessed[2].

Relying on a grid as a frame of reference offers a solution that addresses the described needs. Our proposed solution is based on a 3×3 grid that mimics the layout of the telephone keypad (see Figure 2). The layout of the telephone keypad addresses the important need for a familiar interface that any blind user can recognize and immediately use. The grid introduces nine fixed regions with unique center points, where one is the top left corner and nine is the bottom right corner of the drawing area. The

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[2] For the purposes of this paper, we are addressing drawing in terms of points and lines. However, useful tools should combine these simple elements into sophisticated, content-rich images (e.g., images with circles and polygons).

Figure 2. 3×3 grid of cells

grid can be used recursively inside each of the nine regions to allow finer-grained point selections.

Our research methodology is to carry out user studies to inform technology. The goal of this paper is to communicate why existing drawing methods do not meet the needs of blind users and to propose a new metaphor, the grid, that can be used to overcome many of the difficulties posed by this problem. We believe these findings and recommendations should be useful to others developing drawing tools. The complete description of a tool embodying the grid metaphor and its evaluation is beyond the scope of this paper. In the rest of this paper, we first explore in more detail the problems with existing methods of drawing. Next, we give an overview of the related work in providing graphical access for blind users. This is followed by a description of the tactile drawing study we ran and a discussion of the properties necessary for an effective drawing program. We conclude with our proposal for a grid-based model that includes many of these properties and describe how we have used it in a prototype drawing program for the blind.

PROBLEMS WITH EXISTING METHODS OF IMAGE CREATION AND COMMUNICATION

In this section, we discuss the limitations of three different methods of drawing and graphical communication for blind users: static graphics, tactile freehand drawing, and Computer Aided Design.

Limitations of Static Graphics

It is common to make graphical information accessible to blind people using static systems such as tactile "hard copy" images produced from swell paper (see Figure 1) [6] or molded plastic [22]. Braille labels can also be embedded in or attached to different points on a static image so that blind users can access more information about the image. While tracing the image with one's finger to build a mental model is straightforward, there are prohibitive reproduction costs associated with this technology and it offers no way for a blind individual to edit the image. In addition, physical, static images are tedious to transport, store, and index.

There are ways to overcome these disadvantages, but they are costly. For example, the Nomad mentor [15] audio-tactile graphics tool increases the limited information content by storing text pertaining to the image in a
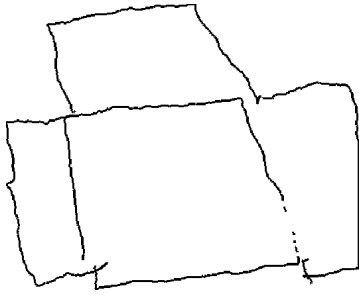
Figure 3. Cube drawn using a tactile drawing tool (T-Draw). This figure is reproduced from Figure 9 in [12].

computer. The image can be placed on a touch-sensitive tablet, permitting access via voice synthesis to the associated text. However, this requires the user to purchase a tablet, possibly a prohibitive expense. In contrast, electronic images are easy to annotate, edit, modify, and reproduce in any quantity or scale. They are also easily transported. We discuss these advantages further below.

Limitations of Tactile Freehand Drawing
Pressing a heat-generating stylus into swell paper makes an impression that can be accessed by touch [19]. We call this method of creating static images *tactile freehand drawing*. Tactile drawing provides no easy way to evaluate the length of a line, assess the curvature of a line, determine an angle, or help close a figure properly. A blind person is unable to freehand draw well using this drawing method.

Figure 3 illustrates a cube that was drawn using a tactile freehand drawing tool [12]. Notice how the lines are not straight, but halting and crooked. The freehand cube illustrates the user's inability to evaluate the length of lines due to the lack of proper feedback. In trying to create a 3D effect, the blind person was unable to attach the sides of the cube, instead creating what seems to be a cube with open doors. The freehand drawing of the cube also illustrates how a blind person is unable to accurately draw the angles needed to represent perspective. The most noticeable deficiency in the tactile freehand drawing is the blind person's inability to connect lines at critical points.

Limitations of Existing CAD Programs
Current CAD programs lack sufficient voice feedback. Screen access programs, such as Outspoken [2], can use ASCII values and Optical Character Recognition (OCR) algorithms to interpret text-based data, while using limited libraries of graphical data to understand common graphical constructs, such as icons and windows. But, because of the inability of screen access programs to interpret graphical data output from traditional drawing software, visually impaired users are unable to use these programs. One suggested solution is to have a "screen reader" capture the value of the graphical data at the lexical level of the application rather than using a pixel-by-pixel translation of the screen contents [14].

Additionally, current CAD programs require external input and output devices that offer the user neither mobility nor

flexibility. Haptic devices, such as the Phantom [21], allow users to "feel" an object or image in three dimensions using a stylus with force-feedback. Tactile displays, another class of output device, interpret images as raised points on a flat surface. Both of these devices are expensive, often costing more than the computer equipment used with them. Like other external devices, they also limit a user's mobility.

RELATED WORK
Previous work on adaptive drawing tools falls into two main categories: accessing graphical data and creating graphical data. Accessing graphical data depends on the method of output (e.g., using haptic displays, tactile displays, or audio-tactile graphics). When creating graphical data, both the method of input and the method of feedback can differ from program to program. In this section, we will examine the methods employed to access and create graphical data in drawing tools for blind users.

Accessing Graphical Data
Voice synthesizers, non-speech sounds, and tactile or haptic displays give blind users access to graphical data. Mynatt, for example, extensively studied results from usability testing of different sound sets used for navigating through standard X-Windows applications [14]. Similarly, Alty used music as the feedback for navigating through an image [3]. The system uses a 40×40 grid and assigns different musical instruments to the x and y axes. This feedback may be difficult to comprehend for users who are not musically trained.

Vanderheiden created a new technique called the "Talking Fingertip" which gives blind people access to university information using an information kiosk [23]. The user touches the screen to access information. Through hybrid haptic and auditory techniques the user navigates through menus, buttons, etc. Elements on the screen that provide information or are associated with actions are identified by auditory verbal names. An auditory verbal description of the screen is heard when an invisible button on the upper left-hand corner is touched. A click is heard when you enter and exit an object. When entering an object the verbal name of the object is presented. For complex screens a hierarchical structure is used. This system combines graphical and textual information. Even though the voice feedback may offer guidance for blind users to locate a graphical object, the system lacks precise guidance. For users to locate a particular object, they may have to run their fingers over many spots on the screen before reaching a desired object. This is time consuming and inefficient.

Creating Graphical Data
T-Draw [12] was one of the first tools used to study how blind people perceive the world they live in. Kurze used a Thermostift digitizing tablet and heat-sensitive swell paper as a method of input. The swell paper is placed on the top of the tablet. Speech recognition is used to simulate keyboard commands. The drawing is constrained to two geometric objects: polygons and lines or sequences. While

the object is being drawn, its attribute (name) is given verbally by the user. A polygon is recognized when a line ends near the beginning of another line and a voice command is given. The drawing can be explored by using a tablet and a special pen. When the pen approaches a line or is inside a polygon, the associated attributes are described using a text-to-speech system. This method does not allow drawings to be altered later, and most importantly it does not compensate for lack of visual feedback. A feedback mechanism that compensates for lack of vision is absolutely necessary when mimicking drawing with pencil on paper. For example, drawing two parallel lines (i.e., maintaining the same angle) is hard to achieve using T-Draw and similar commercially produced devices [18].

TACTILE DRAWING USER STUDY

We performed a tactile drawing study to explore the limitations of drawing without visual feedback and to better understand what types of feedback a drawing program for blind users must include. We hypothesized that drawing tools for blind users that simply adapt methods used by sighted users are not sophisticated enough to compensate for a lack of visual feedback. The goal of this study was not to see whether blind individuals could produce the same figures that a sighted person might produce, but instead to see if they could produce what they intended.

We asked visually impaired participants to draw using a Sewell raised line drawing kit [22]. This kit includes a hard clipboard that is coated with a rubber surface. A sheet of plastic is fixed with clamps on top of the board. The user draws on the plastic sheet with an inkless stylus, and the process of the stylus pressing into the rubber-coated surface creates an impression on the plastic sheet.

Method

The study was conducted at a local school for the blind (The Orientation Center for the Blind, Albany, CA). Three blindfolded partially sighted participants and two totally blind participants (see Table 1) were asked to complete four tasks. We explained that the goal was not to test their artistic talent, but the functionality of the drawing tool they were using. Participants were allowed as much time as desired to complete each task. We did not give any hints and the participants were told to use their own interpretation of what the figures should look like. When participants asked questions while drawing, they were told to use their personal judgment. Any comments made while drawing were recorded for later review.

After completing all of the tasks, those who were partially sighted were asked to remove the blindfolds and look at their own drawings. All of the participants were asked to provide comparisons of what they drew with what they intended to draw. The totally blind participants were asked to make their comparison using touch. We videotaped the drawing sessions for further analysis. After completing their sessions, we asked the participants what difficulties

Participant #	Age	Vision Status
1	18	Low vision
2	40	Low vision
3	42	Low vision
4	21	Totally blind for 1 year
5	20	Totally blind since birth

Table 1. Age and visual capabilities of study participants

they encountered while drawing and if they had any suggestions to help overcome any problems they had.

The first task was to draw an uppercase "D." The second task was to draw two greater-than signs (">") on the same page, one a replica of the other. The third task was to draw two squares on the same page, one a replica of the other. The fourth task was a free drawing exercise. Drawing an uppercase "D" assessed the participant's ability to draw a curve and close a figure properly. Drawing two greater-than symbols revealed the ability of a non-sighted user to determine the length of a line and angle between two lines. Drawing two squares also revealed the user's ability to determine length of a line, replicate a right angle, and close a figure properly. The free drawing exercise was conducted to see how other visual information was translated by tactile drawing.

Results

The first participant, who has low vision (R 20/400, L 20/400), successfully drew the uppercase "D." However, upon seeing what he drew after removing the blindfold, exclaimed it was not the shape he had intended (see 4a). Even though the figure may look like a good "D" to an observer, according to what he had in mind, the curvature was wrong. He intended to draw the curvature to look more like a "half tear drop." He said "…going straight down from top to bottom is fine. But when I drew from the left to right and curved down, it looks like I curved too much. It's too wide of a curve. The bottom is too rounded."
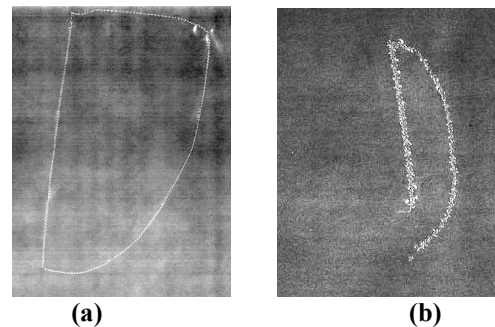

(a)   (b)

Figure 4. Tactile drawing. (a) After drawing the "D," Participant #1 said, "The curvature is not what I had in mind. I wanted it to look like a half tear drop" and (b) participant #4 drew a "D" that was not closed properly at the bottom.

Tactile freehand drawing provides no feedback function to target an abstract point in relation to the drawing. When participant four, who has been totally blind for a year, tried to close the uppercase "D," the participant was unable to target the point of closure for the figure (i.e., the starting point). After completion of the task, the participant was asked, "Does this 'D' look like what you had in mind?" To which the totally blind participant responded after touching the drawing, "Not exactly. It did not connect all the way." (See Figure 4b.) Two of the remaining three participants had similar problems in closing the "D."

On the second task, the first and second participants, who are low visioned and were blindfolded, had to repeat their greater-than signs on a second sheet of plastic. They had over estimated the size of the sheet of plastic on their first attempt. The greater-than signs of two of the participants ended up being drawn at different scales.

After drawing the two squares for task three and removing the blindfold, participant three, who is low visioned, commented, "The square size is what I had in mind. I did not know that the top left corner of the bottom one would be sharp and up a little." She continued, "probably when I moved the pen over to the right, I moved it to the top instead of keeping it straight." (See Figure 5a).

Three out of the five participants came up with alternative methods for drawing the lines of the squares to compensate for lack of visual feedback. One participant counted out loud to five each time he drew a line, another used the length between her thumb and pinky, and another measured using the length of her knuckles to draw lines of equal length (see Figure 5). The different methods for evaluating the length of a line had varying amounts of success.

Participant five, who has been totally blind since birth, used the knuckle method just mentioned above, to determine the length of a line while drawing it. Her first square turned out more like a rectangle: the horizontal lines, while approximately the same length, were longer than the vertical lines. The bottom square drawn by participant five did not match the rectangular shape of the top one; its bottom line was tilted up and was longer than the rest (see Figure 5c). Participant four, totally blind for nearly a year, used a method in which he counted out loud from one to five while drawing each line of two squares. The top square turned out more like a rectangle, but the second square appeared nearly perfect (see Figure 5b).

In the last task, the participants drew whatever they chose. For example, participant 3, who is low visioned, drew a pig (see Figure 6). She was unaware that she drew two of the feet in the wrong place (on the head). She said, "Yes. It looks a little sloppier than what I had in mind. The feet are where they should not be." She also noted that the eyes were supposed to be horizontally aligned. In general, the participants were fairly happy with these images. This may be because there were no real constraints they had to meet, as when asked to draw a square.

Discussion

Analysis of the above results show that a successful drawing model must provide a way to:

Property 1) **target an abstract point in relation to the drawing**, for example, when trying to direct the pen towards a point that is being sensed by the non-dominant hand (i.e., closing the "D" in Figure 4b).

When closing figures, two of the participants attempted to place one hand at the closing position while drawing with the other hand. This technique was not successful. Most of the participants closed the figures either too early or too late, missing the target point. This shows that a mechanism for guiding the user to locate a previously selected point is essential.

Property 2) **evaluate the length of a line**, for example, when trying to make a square with equal length sides (see Figures 5b and 5c)

Clearly, a drawing tool must incorporate a reliable method for measuring the length of a line. The fact that some participants used different methods of measurement suggests that a feedback mechanism to
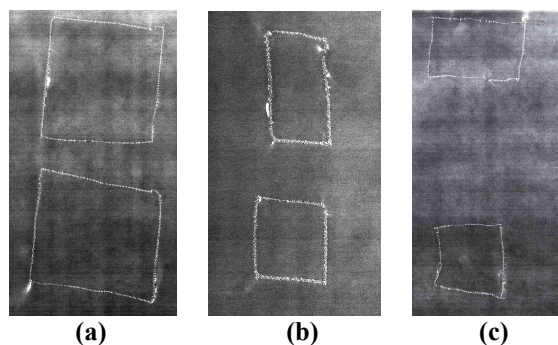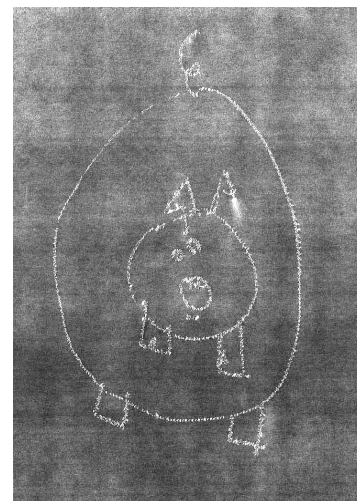

Figure 5. Tactile drawing. (a) Measuring length while drawing using distance between thumb and pinky, (b) using a counting method, and (c) using knuckles.

Figure 6. Participant 3 drew a pig with a Sewell drawing kit.

assess lengths while drawing is required. The counting method seemed to be the most successful. If a user is able to count units of equivalent measure, whether they are units of finger length or time or units on a grid, the relative length of a line can be determined.

Property 3) **assess the curvature of a drawing**, for example, when trying to make a symmetric curve (see Figure 4a)

An object can be drawn in different ways and still map to the same concept. For example, participant one drew a letter "D" that was recognizable, yet incorrect. This result suggests that a drawing tool should incorporate a mechanism to allow the user to assess curvature to get the desired effect.

Property 4) **determine angles**, for example, when trying to draw greater-than signs or make a rectangle with 90 degree corners (see Figure 5c).

No special methods were undertaken by the participants to maintain the same angle during the experiment (drawing two squares). This shows in their inability to make perfect squares. A drawing tool should incorporate the ability to assess and maintain the same angle in different parts of a drawing.

These properties are essential for both making drawings that match users mental models and for *interpreting* existing drawings. Electronic drawing tools can include functionality supporting these properties.

A GRID-BASED MODEL FOR DRAWING

The above results suggested several properties that are necessary in designing any successful drawing program for blind users. We believe that a grid-based model of input supports these properties. In this section we first describe the valuable features of this model, describe how the model can be used to draw figures, and conclude with a discussion of the benefits and the generality of the model.

Why a Grid?

In the "Design of Everyday Things'' [16], Don Norman identifies two important attributes of good designs: the user should be able to figure out what to do, and the user should be able to recognize what is going on. The challenge of designing any new method for accomplishing a task is adapting the method to the intended user's intuition so that these two properties hold true. This fact is recognized in existing methods of accomplishing tasks where, possibly unintended by the original designers, users have adopted a familiar interface to a new tool or method.

A clock face is an example of a familiar interface adopted by users to accomplish various tasks. For example, blind users can use this interface to locate different types of food on a plate. The positions of numbers on a clock face can be associated to the position of food on the plate relative to
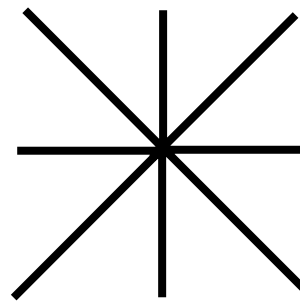

Figure 7. Point relocation is necessary to draw a data network with the star topology pattern.

other types of food on the same plate. The vegetables might be at "3 o'clock" on the plate.

Learnability and Memorability

Similarly, blind individuals are trained early on to memorize the layout of the telephone keypad. This is one of the most important skills they learn to permit independent living. This familiarization with the keypad layout is the most valuable feature of our grid-based metaphor. This is not the first time a grid has been used in drawing. For example, grids have been used to teach beginners how to draw and to enlarge and scale drawings by using different sized grids [1].

Relocating Points

When drawing, the ability to locate and relocate a point is essential. The aim is to allow a blind person to select a desired point, move to a new location to perform another task, and later relocate points and properly close figures using the original point. To demonstrate the importance of relocating an exact position, consider the "star topology" of a data network. The star topology consists of an origin point and rays emanating from it. After drawing the origin and the first ray, the blind user must find the origin again to attach each of the subsequent rays (see Figure 7). This example demonstrates the significance of relocating the exact position of a point or a line [11]. Approximate relocation of a given point is often inadequate. Knowing which cell the origin of the star topology was located in would allow this relocation.

The layout of the telephone keypad divides a space into discrete parts. A continuous medium can be managed in terms of numbered cells whose relative positions have meaning through recognition of the association to the numbered layout of a telephone keypad. The ability to manage discrete parts of an abstract space allows for the user to locate an abstract point or to relocate an exact point within the space (property 1 above).

A blind user must also be able to conceptually relate absolute and relative positions of the drawing scene. For example, to close the "D," the user needs to know the relative position of the pen with respect to the absolute position of a previously drawn object. Again, knowing the grid location of the previous object and the grid location of the cursor gives the user this information.
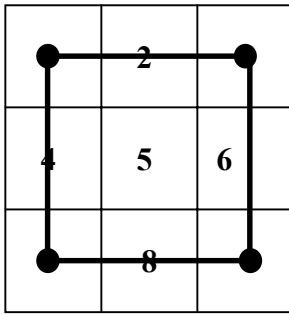
Figure 8. Using a grid to create a square by connecting the four corners of the square with lines.

Figure 9. The IC2D shape palette also uses a grid.

Creating Equal Length Lines and Angles

Drawing often requires the user to make parallel lines of equal length, as in the case of the square. Some guideline or frame of reference is needed. Again, the grid solves this problem. The user knows which cells are located horizontally or vertically across from one another and can thus draw lines of equal length (property 2).

This same frame of reference also must offer a mechanism to direct the angle of a line being drawn or to describe the angle of a line being accessed, as this is necessary for correctly drawing a greater-than sign. Again, knowing the relative position of the grid cells, a user can maintain the same angle across a drawing (property 4).

Maintaining Curvature

The grid does not offer any fundamental support for maintaining curvature, but by supporting primitive-based 2D graphics on the grid, he or she is permitted to use objects that maintain the proper symmetric curvature by definition (e.g., arcs, ellipses, or circles). This helps fulfill property 3.

Using a Grid to Draw and Select From Menus

Now we will show how to draw a square using IC2D [10], a drawing program for the visually impaired. IC2D uses a grid, offering the user the properties discussed previously. A keyboard is used to navigate the grid, select points, and draw shapes. Voice feedback is used to communicate the current position in the grid as well as the attributes of the current drawing mode.

To draw a square using IC2D, we maintain the proper lengths of the sides by connecting points with lines. To draw the top of the square, we select cells 1 and 3 in the IC2D grid as the two end points of the top line and then issue a draw-line command joining both of the selected points (see Figure 8). To achieve this, first we move to cell 1 and select it. We move the cursor to the right two cells and then select cell 3. Next, we access the shape palette (see Figure 9). Here, we use the same navigation keys to select from a set of available shapes laid out in a grid. When we reach the line object, voice feedback identifies it as a line, we select it, returning us to draw mode. To render the top line of the square, we press the "d" key for "draw." There are two ways to draw the remaining three sides. The user can repeat the above steps for the right (3, 9) bottom (9,7), and left (7, 1) sides of the square. Alternatively, the
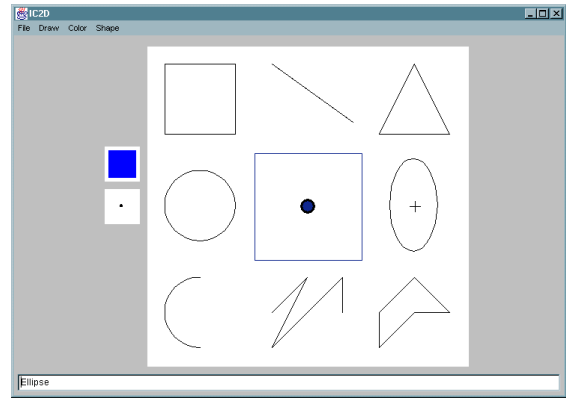
user can select 3, 9, 7, and 1 in order and then select the multi-line object from the shape palette

Generality and Benefits of the Grid-Based Model

The grid-based model assists blind users in exploring graphics by giving a mental model of the position of objects. The grid-based model can also be integrated with existing drawing tools such as pen-based tactile and non-tactile devices [20, 22], speech [14], and musical tones [3, 5] to provide an overall structure of the drawing scene.

With a tablet and a keyboard, the grid-based model could be used with tactile drawing tools to make it easier to register information associated with graphical data [15]. It could also be utilized in systems that replace direct manipulation techniques with information presented via auditory methods [17]. For example, the telephone keypad, in combination with audio feedback, has enabled non-sighted and sighted users alike to access e-mail and the graphically rich content of the World Wide Web [8].

One of the authors, blind since the age of 23, used IC2D to create the cube shown in Figure 10. This figure recreates the cube drawn in Figure 3, but since the user has used a grid, he is able to evaluate the length of lines, determine and recreate angles, and close the figure properly. The IC2D prototype has also been used by three other blind
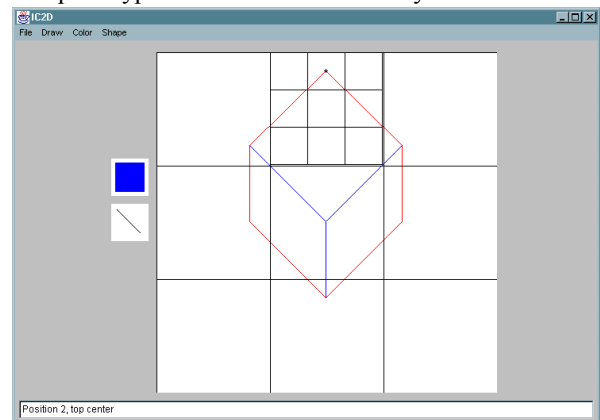

Figure 10. Cube drawn by a blind user using IC2D. Note that the grid can be used recursively to get a finer resolution of point selection.

users in a pilot study to draw figures as complex as a car (see [10]).

The key to the grid-based model and IC2D is not the ability to create primitive shapes – any drawing program tool has this capability. The key is the way that these primitives can be combined and modified over time because the grid allows blind users to find these objects after they are drawn, relocate the important control points on the objects, and subsequently modify or connect new objects to these important points. This same technique could also be used to identify the key points in a freehand drawing, e.g. the start and endpoints of a given stroke.

CONCLUSION

Our study of tactile freehand drawing showed that existing drawing tools for blind users lack proper feedback. The results suggest a set of properties that would provide the necessary feedback in any drawing medium. We have also described a grid-based model that supports these properties, significantly improving the usability of graphical tools in a non-visual environment. This model permits blind users to easily select points, locate them later, measure equal lengths, replicate angles and properly close figures. This same model can be used for navigation in other settings, such as in menu selection.

End users often differ greatly from designers and this difference is sometimes underestimated. Our long-term goal is to provide an effective drawing tool for blind individuals, enabling them to survive in a graphics-based world. We believe such a tool will greatly improve the communication of blind users' mental models of the real world.

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REFERENCES

1. *Sample Lesson: Basic Drawing Using a Grid*. http://www.homeschoolarts.com/samplelesson.htm
2. Alava, *outspoken 3.0*. Alava Access Group. http://www.aagi.com/aagi/news04.html
3. Alty, J.L. and D.I. Rigas. Communicating Graphical Information to Blind Users Using Music: The Role of Context. In Proceedings of *ACM Conference on Human Factors in Computing Systems: CHI '98*. pp. 574-581 1998.
4. Boyd, L.H., W.L. Boyd, and G.C. Vanderheiden, The Graphical User Interface: Crisis, Danger, and Opportunity. *Journal of Visual Impairment and Blindness*, 1990(December): p. 496-502.
5. Brewster, S. and M. Crease. Making Menus Musical. In Proceedings of *INTERACT '97*. pp. 386-396 1997.
6. Edman, P., *Tactile Graphics*. New York: American Foundation for the Blind, 1992.
7. Edwards, A., A. Edwards, and E. Mynatt. Tutorial: Enabling Technology For Users With Special Needs. In Proceedings of *Human Factors in Computing Systems: CHI '94*. pp. 405-406 1994.
8. Goose, S., M. Wynblatt, and H. Mollenhouer. 1-800-Hypertext: Browsing Hypertext with a Telephone. In Proceedings of *Ninth ACM Conference on Hypertext*. pp. 287-288 1998.
9. Griffeth, N. Making a Simple Interface Complex: Interactions among Telephone Features. In Proceedings of *ACM CHI '96 Conference on Human Factors in Computing System*. pp. 244-245 1996.
10. Kamel, H.M. and J.A. Landay. The Integrated Communication 2 Draw (IC2D): A Drawing Program for the Visually Impaired. In Proceedings of *ACM Conference on Human Factors in Computing Systems: CHI '99*. pp. 222-223 1999.
11. Kinderart.com, *Blind Contour Drawing*. http://www.kinderart.com/drawing/blind.htm
12. Kurze, M. TDraw: A Computer-Based Tactile Drawing Tool for Blind People. In Proceedings of *Second Annual ACM Conference on Assistive Technologies: Assets '96*. pp. 131-138 1996.
13. Millar, S., Visual Experience or Translation Rules? Drawing the Human Figure by Blind and Sighted Children. *Perception*, 1975. **4**(4): p. 363-371.
14. Mynatt, E.D., *Transforming Graphical Interfaces into Auditory Interfaces*, Unpublished Ph.D., Georgia Institute of Technology, Atlanta, Georgia, 1995.
15. Nomad, *Nomad Mentor*. http://www.quantech.com.au/qtpro-nd.html
16. Norman, D., *The Design of Everyday Things*. New York: Doubleday. 108, 1990.
17. Pun, T., P. Roth, and L. Petrucci. An Image-Capable Audio Internet Browser for Facilitating Blind User Access to Digital Libraries. In Proceedings of *3rd ACM Conference on Digital Libraries*. pp. 301-302 1998.
18. Repro-Tronics, *Tactile Graphics Designer*. Repro-Tronics Inc. http://www.tactile-audio.com/
19. Repro-Tronics, *Thermo-Pen I*. Repro-Tronics Inc. http://www.repro-tronics.com/thermo.html
20. Roth, P., et. al. From Dots to Shapes: an auditory haptic game platform for teaching geometry to blind pupils. In Proceedings of *International Conference on Computers Helping People with special Needs: ICCHP 2000*. Karlsruhe, Germany, July 17-21 2000.
21. SensAble, *Phantom*. SensAble Technologies. http://www.sensable.com/products/index.htm
22. Sewell, *Sewell raised line drawing kit*. Sewell Metal Processing Corporation: Woodside, New York 11377.
23. Vanderheiden, G.C. Use of audio-haptic interface techniques to allow nonvisual access to touchscreen appliances. In Proceedings of *Human Factors and Ergonomics Society Annual Conference* 1996.