

# Toward Haptic/Aural Touchscreen Display of Graphical Mathematics for the Education of Blind Students

Jenna L. Toennies\*

Jessica Burgner†

Thomas J. Withrow‡

Robert J. Webster III§

Department of Mechanical Engineering  
Vanderbilt University, Nashville, TN, USA

## ABSTRACT

We propose the use of a haptic touchscreen to convey graphical and mathematical concepts through aural and/or vibratory tactile feedback. We hypothesize that an important application of such a display will be in teaching visually impaired students concepts that are traditionally learned almost entirely visually. This paper describes initial feasibility studies using a commercially available haptic touchscreen to display grids, points, lines, and shapes – some of the first visual graphical entities students encounter in K–12 mathematics education, and from which more complex lessons can be constructed. We conducted user studies designed to evaluate perception of these objects through haptic feedback alone, auditory feedback alone, and combinations of the two. Our results indicate that both sensory channels can be valuable in user perception.

**Index Terms:** Haptic Touchscreen, Haptic and Auditory Feedback, Math Education, Blind and Visually Impaired

## 1 INTRODUCTION

From small handheld devices to large industrial consoles, touchscreens are rapidly becoming common interfaces, allowing people to interact with information using their fingertips. To enable touchscreens to provide a more interactive user experience, there has been an increasing recent interest in incorporating tactile haptic feedback into these devices (see e.g. [6], [17]). Such haptic – typically vibratory – feedback is designed to enable the user to “feel” virtual objects (e.g. the click of a button). This is particularly useful when user attention is or can be diverted from the touchscreen due to multitasking or interruptions [17]. A number of different technologies have been explored over the past few years to endow touchscreens with tactile feedback.

Perhaps the simplest way to create vibrotactile feedback is an eccentric mass on the shaft of a motor, a strategy commonly employed in cellular telephones. Other available actuation methods include piezoceramics [17], dielectric elastomers [1], and electrostatics [13]. Alternatives to direct actuation of flat, rigid surfaces are pin arrays actuated by servomotors (see e.g. [25]), piezoelectric bimorphs [10, 28], solenoids [29], and shape memory alloys [22]. It is also possible to use laterally actuated pins that stretch the skin of the finger [16]. While some of these devices have been used to effectively display braille, it is not clear whether they can be adapted to our purpose of displaying objects on a large screen surface in a robust and cost effective manner.

Variable friction displays [6, 27] provide an alternative that can be made larger in area without requiring additional components. These allow users to perceive textures, surface features, and edges

through lateral forces which arise when ultrasonic vibrations of a glass plate are turned off (when turned on, a layer of air is created between the finger and plate, reducing friction).

Haptic feedback is particularly important for educating the visually impaired. According to the World Health Organization, about 314 million people are visually impaired worldwide, 45 million of whom are blind [2]. Several tactile devices have been developed to present graphical and textual information through touch (see [7, 23] for good overviews). These can be grouped into three categories [23]. The first, static refreshable displays, allow users to explore a picture by moving their fingertips over it while the display itself refreshes by raising or lowering pins. One innovative example of a static refreshable device is a custom-built touch sensitive 7200 pin-matrix device that is capable of detecting multiple points of contact [24]. It consists of 720 10-pin vertical Braille modules stacked side by side, with the pins actuated by piezoelectrics. Though graphics can be generated and updated by raising and lowering the pins, it is unclear whether this device will ultimately be sufficiently cost effective for widespread deployment and robust enough for everyday classroom use by children.

A second group of devices designed to display images through touch are dynamic displays, which act on a stationary finger, dynamically updating information displayed to the fingertip. While these devices do not consume as much power as the static refreshable displays, they are also expensive, require more training to learn to use, and are often small in size [23]. Yet a third group of devices designed for tactile display to visually impaired people are the Tactile Vision Substitution Systems, which use a visual input device (e.g. a video camera) combined with a tactile output display to translate visual information into tactile information [23]. While several variations of this type of device have been developed, they are limited to use in exploring static graphics and are often bulky in size [23].

We believe that a portable, refreshable, robust haptic device capable of displaying graphical information has tremendous potential as a tool for mathematical education, particularly for blind and visually impaired students. Current methods of teaching these students can be cumbersome and expensive. Teachers often have to work individually with visually impaired students and must manually construct shapes or graphs on tactile graph paper or using cork boards and pushpins [8, 31]. Another option is to emboss graphical material ahead of time, though this limits interactive learning and precludes answers to questions that stray from the specific lesson plan. An alternative that makes use of purely auditory information transfer is the Accessible Graphic Calculator (ViewPlus Technologies, Corvallis, OR, USA) which converts equations into sounds.

Several researchers have also shown the value of using both haptic (usually force rather than tactile) and auditory feedback to help convey concepts like graphs and shapes to visually impaired students. One approach is to incorporate auditory feedback with force feedback devices such as the SensAble Phantom or Logitech WingMan Force Feedback Mouse to explore and create graphs [5, 18, 30, 31]. Watanabe et al. pursued a different approach, combining a tactile pin-array device, a 3-D digitizer, and a tablet PC

\*e-mail:jenna.l.toennies@vanderbilt.edu

†e-mail:jessica.burgner@vanderbilt.edu

‡e-mail:thomas.j.withrow@vanderbilt.edu

§e-mail:robert.webster@vanderbilt.edu

to allow students to draw and erase lines by moving a stylus along the tactile surface, which they could then explore with their fingertips [26]. Yet another approach used a stylus with an embedded vibration motor in conjunction with a touchscreen to convey a graphical trace to a user [20].

While these prior studies have illustrated the use of haptics in math education, such tools have yet to become commonplace in classrooms. This may be because (with the exception of a few pin-array prototypes, e.g. [24, 26]) they all use force feedback rather than tactile feedback, meaning that the user's interaction with the displayed graphical information is mediated by a stylus or mouse. We hypothesize that there may be perceptual advantages to direct fingertip interaction with the displayed information. Direct contact also has the advantage of direct analogy to visual teaching methods since the plot or graph can be visually displayed on the screen at the same time it is being displayed haptically or through audio information, making it straightforward for sighted teachers to teach blind students. Furthermore, the rapid recent reductions in the cost of touchscreen technology that have spurred the pervasive incorporation of touchscreens into cellular telephones, music players, computers, and other devices, make it likely that widespread future deployment of educational touchscreens will be economically viable. Though current touchscreen technology is largely inaccessible for people with visual impairments [14], a touchscreen that provides tactile feedback has the potential to address this issue and enhance the accessibility of the information being conveyed to the user as well as the user's ability to interact with the touchscreen [4, 9]. Toward illustrating the potential benefits of vibratory touchscreens in education, we explore whether a commercially available vibratory touchscreen (the TouchSense Demonstrator by Immersion Inc., San Jose, CA, USA) can convey graphical concepts such as points, lines, and shapes to human subjects.

## 2 SYSTEM SETUP

Our system consists of two main components: a haptic touchscreen and a laptop computer running our custom software, as shown in Figure 1.

### 2.1 Haptic Touchscreen

Our haptic display consists of the TouchSense Demonstrator - Series 1000, by Immersion, Inc. It consists of a 10.4-inch LCD capacitive touchscreen with 4 Johnson Electric A110 actuators and a TouchSense controller integrated into a package 270 mm × 222 mm × 47 mm, which is similar in size to a laptop computer. The touchscreen itself is 210 mm × 158 mm and allows a resolution of 1024 × 768 pixels. The actuators have a nominal weight of 22 g each and are capable of vibrations of 4 gee at 20 Hz. The surface capacitive touchscreen requires a 5.4 ms minimum finger contact

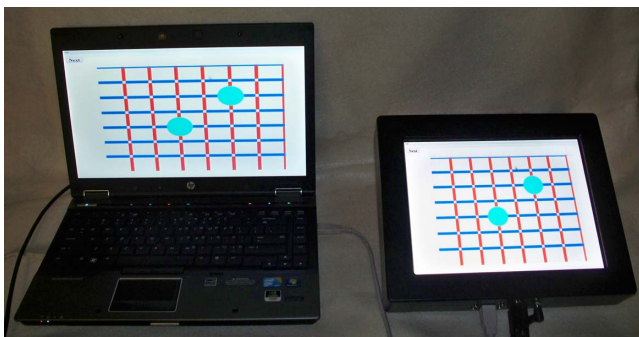


Figure 1: The touchscreen and its host computer displaying a grid with points on it for users to explore and receive haptic and/or auditory feedback.

and is rated for a lifetime of more than 1 million touches. The device operates in conjunction with a PC using 2 USB cables and 1 VGA HDB-15 video cable. Immersion provides the TouchSense API which has 50 built-in haptic effects grouped into 8 base effects classified as pop click, crisp click, pulse click, high frequency click, double click, constant vibration, pulse vibration, and single/double vibration. Within each of these categories, the effects vary in magnitude and duration.

### 2.2 Haptic and Aural Exploration Software

Using Immersion's TouchSense API and the open-source cross-platform application and user interface (UI) framework Qt (Nokia, Oslo, Norway), we developed a multi-threaded application in C++ that allows users to explore touchscreen content with haptic and/or auditory feedback (*Explore Mode*) and to create new drawings easily (*Sketch Mode*).

The system deals with the touchscreen input as with any other user input device (e.g. mouse, touchpad). The input position, i.e. the fingertip location on the screen, is called a touch point. Qt deals with user touch input with the class *QTouchEvent*, which handles a touch event whenever the user presses, releases, or moves his/her finger on the touch device. This allows us to detect the beginning (first occurrence of contact with the display) and end (lifting the finger off the display) of the user touching the screen, and to evaluate the finger position and touch path during the touch. User inputs are processed in the UI thread, which identifies user touch points on the haptic touchscreen and determines the appropriate response.

In *Sketch Mode*, the user can choose either a blank, white input area or a background image of their choice as their "sketch pad." In order to create new learning content for the *Explore Mode*, the user can "sketch" or paint a desired graph or image. In this mode, for every detected touch event, the trace of the user's touch motion is displayed on the screen. The user can choose line width and color and can choose from various geometries to be placed in the image. The user-created learning content can then be saved and opened up in *Explore Mode*.

In *Explore Mode* (Figure 2), the user can choose any image to explore on the touchscreen and can choose between haptic and/or auditory feedback. The UI is the core thread of the *Explore Mode*. Two additional threads handle the haptic and auditory feedback. The haptic thread incorporates the built-in haptic effects of the TouchSense API from Immersion and provides vibratory feedback to the user's finger on the touchscreen. The auditory thread enables the device to play tones with specific frequencies and durations. For each detected touch event, the touch position is determined and the corresponding pixel type of the displayed learning content is evaluated. Each pixel is assigned to a specific feedback sensation, either haptic or auditory or both, allowing the user to distinguish between different content. The white background is assigned to no feedback sensation.

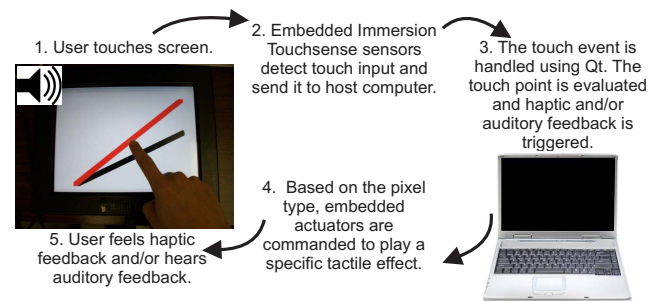


Figure 2: The basic program workflow for the *Explore Mode* of the touchscreen.

### 3 EXPERIMENTAL METHODS

To explore touchscreen display of basic math concepts, we conducted two experiments. One was designed to evaluate whether users could find desired Cartesian  $(x,y)$  locations and identify points on a grid. The second evaluated whether users could differentiate between shapes and lines of varying slopes. These represent some of the first graphical concepts taught to children, and they are generally presented visually. Points and lines are typically introduced at the beginning of algebra (6th or 7th grade) and are considered fundamental concepts [3]. Our experiments were designed to evaluate both haptic and auditory feedback, and combinations of the two.

The user studies discussed below were performed on sighted individuals ( $N = 10$ , mean age 27, two left-handed, two female). The studies were completed in two sessions conducted within 1-5 days of one another. Half of the users were randomly assigned to perform the haptic grid session first, and the other half performed the auditory grid session first. On each grid, users first navigated to desired  $(x,y)$  locations (Section 3.1.2), and then identified and located both haptic and auditory points that were displayed (Section 3.1.3). In the session with the haptic grid, subjects also performed the shape/line discrimination experiment (Section 3.2) with haptic feedback. Similarly, in the session with the auditory grid, they performed shape/line discrimination with auditory feedback. During the parts of these experiments that involved all haptic feedback, users listened to background music of their choice and wore sound isolating earmuffs to mask the sounds of the touchscreen actuators. During portions that involved combined haptic and auditory feedback, users wore the earmuffs and also listened to white noise. The earmuffs were not required during the purely auditory feedback portions of the experiments.

During all experiments, the touchscreen itself was shielded from the user's view by a box with an opening at the front, allowing them to touch the touchscreen without viewing it (Figure 3). Users were allowed only one point of contact with the screen in all studies. This was verified by the experimenter watching the user's touch point cursor on the host computer monitor. If a user touched the screen with more than one finger, this cursor would move erratically on the screen, in which case the user was reminded to only use one finger for exploration.



Figure 3: A user interacting with the touchscreen during the user studies. The user was able to touch the screen, but not view it, and the user's ears were shielded to prevent auditory feedback from touchscreen actuators during haptic experiments.

#### 3.1 Point/Coordinate Location Experiment

In this experiment, we sought to answer 3 questions: (1) Can users navigate to a given  $(x,y)$  location on a grid, (2) Can users find dis-

played points on a grid, and (3) Can users determine the  $(x,y)$  location of these points on a grid.

##### 3.1.1 Experimental Setup and Grid Display

To investigate these questions, we created figures in Matlab (Mathworks, Natick, MA, USA) of  $7 \times 7$  grids, both with and without points on them, as shown in Figure 4. The total grid area was 157.5 mm wide ( $x$ ) by 126 mm tall ( $y$ ), meaning that each physical grid unit was 19.5 mm ( $x$ )  $\times$  15 mm ( $y$ ). Grids that contained points contained two points located randomly at grid intersections. Points were displayed as 22.5 mm diameter circles.

In order to help the user discriminate between the grid lines, all of the horizontal grid lines were displayed using one haptic or auditory effect, and all of the vertical grid lines were displayed using a different haptic or auditory effect. The horizontal grid lines were displayed using a crisp click with a relative magnitude of 10 out of 10 and a duration of 50 ms in the haptic session, and a repeating beep of 400 Hz with a duration of 100 ms in the auditory session. The vertical grid lines were displayed using a pop click with a relative magnitude of 4.5 out of 10 and a 10 ms duration in the haptic session, and a repeating beep of 500 Hz with a duration of 50 ms in the auditory session. Both vertical and horizontal grid lines had a thickness of 3.5 mm. To remove ambiguity exactly at grid intersections, no effect was displayed. To ensure that users had a fixed reference for where the entire grid was located on the screen at all times, we attached thin strips of transparent vinyl cling around the perimeter of the grid (each 3.5 mm thick), and placed a circle (12.5 mm in diameter) of the vinyl cling at the origin, as illustrated by the black lines and circles in Figures 4 and 5.

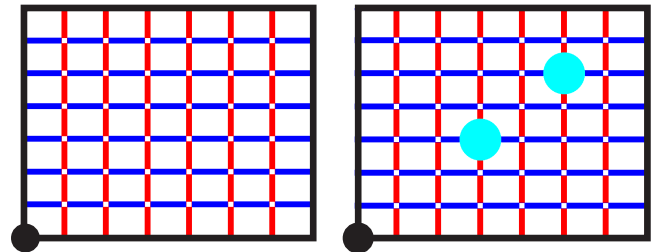


Figure 4: Examples of the information displayed to the user in the Point/Coordinate Location Experiment (Section 3.1). The black lines and circle represent the vinyl cling attached to the screen to create raised physical borders and an origin for the grid. (Left) A blank grid. (Right) A grid with two points displayed.

##### 3.1.2 Finding a Desired Point

To determine whether users could find a desired coordinate on the grid, we conducted the following experiment. We introduced users to the grid with an initial training period where no data was recorded. During this period, they were first allowed to explore only vertical grid lines with horizontal lines turned off, and then horizontal lines with vertical lines turned off. In both cases, they were verbally told what was being displayed, and they were allowed to explore it for as long as they liked. Next, the complete grid was displayed, and users were instructed to familiarize themselves with the grid and determine its size. During this part of the training, the experimenter provided verbal feedback to the user on whether or not the grid size was determined correctly. If the user did not correctly identify the grid size, the experimenter provided verbal assistance as necessary until the user determined the grid to be  $7 \times 7$ . All of these training procedures were designed to familiarize the subject with the device, and all were structured such that they could be conducted in exactly the same manner with blind subjects.

Next, the user was given a specific (x,y) point location verbally and was instructed to find it on the grid, as shown in Figure 4 (Left). Between one and three practice trials were performed until the user was comfortable with the task. In these, users received verbal feedback on whether or not they reached the correct location and were told what location they had actually reached if they had reached an incorrect location. The location reached was identified as the closest grid intersection to the user's position when they indicated that they had reached their desired location. After the practice trials were completed, three trials were performed, in which the experimenter provided no feedback or assistance, and recorded whether the correct or incorrect final location was achieved. Results of this coordinate finding experiment are shown in Table 1 and discussed in Section 4.

### 3.1.3 Identifying a Displayed Point

After users had completed the location finding experiment described above, they were then asked to identify and determine the locations of points displayed on the grid, as shown in Figure 4 (Right). Point locations were chosen randomly within (but not on the borders of) the grid. In the combined cases where a haptic point was displayed on an audio grid and vice versa, points were displayed with constant vibration of relative magnitude of 6 out of 10 and a duration of 45 ms, or a repeating beep of 600 Hz with a duration of 275 ms, respectively.

To familiarize the user with the method of displaying points, two points were first displayed without the grid, and the user was allowed to explore the screen. Two points were then displayed together with the grid, and the user was asked to find the points and determine their locations with respect to the grid. One to two practice trials of this procedure were completed to make sure the user understood the task. During the practice trials, users received verbal feedback and assistance if needed. After this training procedure, the experiment commenced, during which the experimenter provided no verbal feedback. In the experiment, subjects identified 6 points in total, in groups of two at a time. This process was done for both haptic and auditory points in both the haptic grid session and the auditory grid session. Results are shown in Table 2 and discussed in Section 4.

## 3.2 Shape and Line Discrimination Experiment

In the second set of experiments, we explored: (1) Can users differentiate between shapes and lines, (2) Can users determine the general slope of a line, and (3) Can users perceive different shapes. To investigate these questions, we created 3 figures in Matlab of single lines (5 mm thick) having a slope of 22.5°, 45°, or 67.5°. No grid was displayed in these figures, but the vinyl cling axes and origin remained on the screen, affixed as previously described. Using Corel Draw (Ottawa, Canada), we also created 3 figures, one each of a filled circle, a filled square, and a filled triangle. All of the shapes were approximately the same size and were located at the center of the screen.

In this experiment, users were instructed to explore the screen and then verbally classify what they felt as being one of 6 different objects: (1) a line with slope less than 45°, (2) a line with slope greater than 45°, (3) a line with slope equal to 45°, (4) a circle, (5) a square, or (6) a triangle. The images displayed on the touchscreen for each are shown in Figure 5. Users first completed one practice trial, in which they were given verbal feedback on whether their answer was correct or incorrect and were told the correct answer if they responded incorrectly. The experiment then commenced, during which no verbal feedback was provided by the experimenter. The experiment consisted of twelve object presentations to the user, with each object displayed twice and the order of presentation randomized. Users were not told how many objects would be presented or that each figure option would be presented twice. Ob-

jects were presented using haptic feedback during the haptic grid session, and auditory feedback during the auditory grid session, although no grids were displayed in the shape and line discrimination experiment. The type of haptic or auditory feedback (magnitudes, durations, tones, etc.) were the same as those used for the vertical lines of the grids in the previous set of experiments. Results are shown in Table 3 and discussed in Section 4.

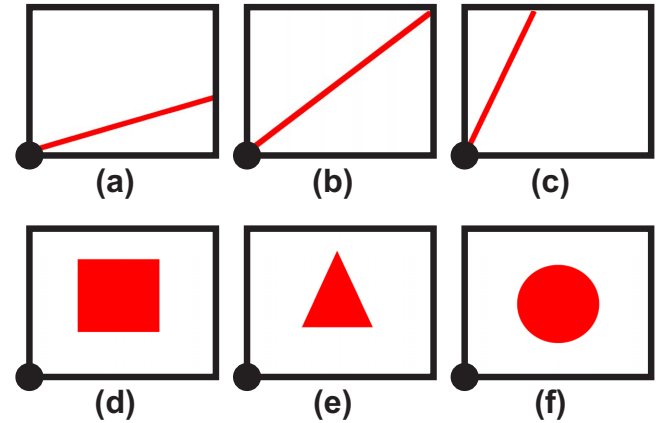


Figure 5: The figures which were displayed on the touchscreen to users in the Shape and Line Discrimination Experiment (Section 3.2). The lines displayed have a slope of (a) 22.5°, (b) 45°, and (c) 67.5°. The shapes displayed were either (d) a square, (e) a triangle, or (f) a circle. Users were to describe what they felt and then state if it was a line less than, equal to, or greater than 45° or if it was a square, triangle, or circle.

## 4 EXPERIMENTAL RESULTS

Results of the experiments are presented in the order they were discussed in Section 3. For the first part of the Point/Coordinate Location Experiment, finding a desired Cartesian location (Section 3.1.2), the mean and standard deviation of the correct number of locations (out of 3) found by the users on both the haptic and auditory grid are shown in Table 1.

Table 1: The mean and standard deviation ( $\sigma$ ) of the correct number of locations reached by users (out of 3) for both the haptic grid and the auditory grid for the first part of the Point/Coordinate Location Experiment, finding a desired point (see Section 3.1.2).

	Haptic Grid	Auditory Grid
Mean	2.30	2.10
$\sigma$	0.82	0.88

From these results, we can see that users were able to reach the correct location over 66% of the time in both cases. To determine if there was a significant difference between the haptic grid and auditory grid, we performed a Wilcoxon Signed Rank Test with continuity correction and obtained a p-value of 0.68. This suggests that there was no statistically significant difference between user performance with haptic vs. auditory grids in our experiment.

For the second part of the Point/Coordinate Location Experiment, identifying a displayed point (Section 3.1.3), all users were able to successfully find all of the points, regardless of the feedback mode of the points or the grid. Thus, a total of 240/240 points (10 subjects  $\times$  6 points  $\times$  4 cases) were found. Results for the correct number of (x,y) locations (out of 6) determined by the users are shown in Table 2. We tested for significant differences between

each of the four cases using a Wilcoxon Signed Rank Test with continuity correction, but found none at the 0.1 level or below. Users performed very well in each of the four cases presented with 8 out of the 10 users being able to determine the correct (x,y) location for at least 5 of the 6 points. We note, however, that these 8 users were not the same users in each feedback case.

Table 2: The mean and standard deviation ( $\sigma$ ) of the number of (x,y) point locations correctly identified by users (out of 6) for the haptic grid with haptic points (H,H), the haptic grid with auditory points (H,A), the auditory grid with auditory points (A,A), and the auditory grid with haptic points, (A,H) in the second part of the Point/Coordinate Location Experiment, identifying a displayed point (see Section 3.1.3).

	H,H	H,A	A,A	A,H
Mean	5.4	5.30	5.00	5.30
$\sigma$	1.07	1.06	1.63	1.06

Results for the Shape and Line Discrimination Experiment (Section 3.2) are displayed in Table 3, which shows the mean and standard deviation of the correct number of lines and shapes (each out of 6) identified for both haptic and auditory feedback.

Table 3: The mean and standard deviation ( $\sigma$ ) of the correct number of lines (out of 6) and shapes (out of 6) correctly identified by users for both haptic (H) and auditory (A) feedback for the Shape and Line Discrimination Experiment (see Section 3.2).

	H Lines	H Shapes	A Lines	A Shapes
Mean	5.80	4.00	6.00	4.20
$\sigma$	0.42	1.15	0	1.55

In both cases, we observe that users were able to differentiate lines from shapes more accurately. A Wilcoxon Signed Rank Test with continuity correction suggests a significant difference between the correct number of lines and shapes identified in both cases (haptic p-value=0.01 [95% CI: (1.5, 3.0)] and auditory p-value=0.02 [95% CI: (1.5, 3.5)]). There were not, however, significant differences between haptic lines and auditory lines or haptic shapes and auditory shapes.

## 5 DISCUSSION

The results from these two feasibility studies are encouraging in several regards.

### 5.1 Point/Coordinate Location Results

The results from the first part of this experiment, finding a desired point, indicate that users were able to correctly navigate to a given Cartesian location on the grid over 66% of the time. Based on qualitative observations and user feedback, and considering that this was the user's first exposure to the touchscreen and the grid, we believe that these are promising results, which suggest that the grids as displayed have the potential to be "seen" well through touch by a user.

The results from the second part of this experiment, identifying a displayed point, are even more promising with respect to future use of the device to teach concepts such as points, lines, and slopes to students. The fact that every user found every point on the grid, and that 80% of users correctly determined at least 5 out of 6 coordinate locations of those points, indicates that the desired information was adequately conveyed to the subjects.

The lack of statistically significant differences between auditory and haptic feedback indicates the need for further studies evaluating the relative value of each, and the value of combinations of the two.

Mixed results in terms of a preferred mode of feedback were also found in [19]. Yu et al., however, did find that multimodal (haptic and auditory) representation can enhance a user's ability to interpret graphs using a force feedback device in some cases [30].

Our qualitative assessment based on developing and conducting the touchscreen experiments and interviewing users is that a combination of both haptic and audio cues will likely be more valuable than either stimulus in isolation. In our study, personal preference for haptic vs. auditory feedback was highly variable between users, as was the strength of the preference. It is interesting to note that in a post-study questionnaire users filled out, users rated the ease of finding the points on the grid highest for combined feedback where a haptic grid and auditory points (or vice versa) were used, rather than use of solely haptic or solely auditory feedback.

### 5.2 Shape and Line Discrimination Results

The results from this second experiment suggest that under the criteria given, users were easily able to distinguish lines from shapes. Further, they were also able to discriminate well between the three slope conditions given. It was more challenging for users to discriminate the different shapes from one another. We suspect that shape identification was more challenging partly due to a diversity of exploratory procedures (no specific exploratory procedure was suggested or prescribed in our experiments). For example, one of the more successful strategies employed by some users was to identify a shape by searching for corners, but not all users employed this exploratory procedure. Also, user feedback indicated that it might be useful to enable the user to "mark" features they wished to return to (e.g. the locations of corners or vertices of a shape). Making the touch screen interactive in this way is straightforward and is a promising direction for future development.

## 6 CONCLUSIONS AND FUTURE WORK

In this paper we have described our initial feasibility studies toward developing a touchscreen interface capable of displaying graphical and mathematical concepts to visually impaired users through haptic and/or auditory feedback. Our primary motivation is to assist teachers in educating visually impaired children. Toward this end, we used a commercially available haptic touchscreen and developed a multi-threaded program using Qt and Immersion's TouchSense API to provide haptic and auditory feedback to a user. To evaluate the feasibility of conveying various graphical concepts, we conducted several user studies. These studies showed that it was possible for most users to find specified locations on a grid, determine the locations of displayed points, and differentiate between lines and shapes, with haptic feedback, auditory feedback, and various combinations of the two. While our experiments did not enable us to conclusively determine the best combination of haptic and/or auditory feedback, we believe that both are valuable, and a combination of the two will likely enable maximal information to be delivered to the student in minimal time. An interesting future question will be whether the added benefits we expect from haptic feedback will outweigh the costs associated with equipping a touchscreen with actuators. Further, several researchers have found that the exploration and collection of spatial information differs between sighted and blind people (see e.g. [11, 12, 21]), which poses interesting questions on how the results in this study will compare to future studies involving blind users.

In future work we intend to perform additional user studies toward determining rules for when haptic and/or auditory feedback may be most effective and how to best combine them. We also intend to work with teachers to develop math lessons that make use of the touchscreen in the classroom, for both sighted and blind student groups. One potential benefit we can foresee for touchscreen use is that one teacher may be able to teach a larger number of visually impaired students simultaneously. Rather than having to spend time

at each student's desk individually, recreating a graph or plot manually, the teacher will be able to draw the graph or plot on a screen at the front of the room, and have it immediately appear on the screens of all the students at once. After developing educational modules for the classroom, we plan to compare learning outcomes with control groups taught the same concepts using traditional methods.

In summary, we believe that touchscreens hold great potential for enhancing education in various ways. Sighted students may benefit from interactive modules involving visual touchscreens, visually impaired students will likely benefit from screens that provide touch and/or auditory feedback, and students who are both blind and deaf may benefit from purely haptic touchscreens. Achieving these potential benefits on a large scale will require advancements in display technology, a better psychophysical understanding of user-touchscreen interaction, and well-designed educational materials that take advantage of the capabilities provided by touchscreens. Given their many potential uses in education, as well as the rapidly expanding variety and capability of modern touchscreen technology, touchscreens appear poised to become powerful educational tools in the near future.

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