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A user-centered design and analysis of an electrostatic haptic touchscreen system for students with visual impairments

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ABSTRACT

Students who are visually impaired face unique challenges when learning mathematical concepts due to the visual nature of graphs, charts, tables, and plots. While touchscreens have been explored as a means to assist people with visual impairments in learning mathematical concepts, many devices are not standalone, were not developed with a user-centered design approach, and have not been tested with users who are visually impaired. This research details the user-centered design and analysis of an electrostatic touchscreen system for displaying graph-based visual information to individuals who are visually impaired. Feedback from users and experts within the visually-impaired community informed the iterative development of our software. We conducted a usability study consisting of locating haptic points in order to test the efficacy and efficiency of the system and to determine patterns of user interactions with the touchscreen. The results showed that: (1) participants correctly located haptic points with an accuracy rate of 69.83% and an average time of 15.34 s out of 116 total trials, (2) accuracy increased across trials, (3) efficient patterns of user interaction involved either a systematic approach or a rapid exploration of the screen, and (4) haptic elements placed near the corners of the screen were more easily located. Our user-centered design approach resulted in an intuitive interface for people with visual impairments and laid the foundation for demonstrating this device's potential to depict mathematical data shown in graphs.

1. Introduction

In 2013, approximately 694,000 school-aged individuals in the United States reported some level of visual disability (Erickson et al., 2014). According to the 2014 federal quota census data, 61,739 students are eligible for adapted educational materials through the Act to Promote the Education of the Blind. While some of these students attend schools specifically dedicated to those who are blind, many are educated in the mainstream school system, which are frequently ill-equipped with adequate assistive technologies (American Printing House for the Blind, 2015).

For students who are visually impaired, math and science concepts pose a unique challenge due to the visual nature of data embedded in graphs, charts, tables, and plots (Nam et al., 2012). Tactile models such as embossed paper and pin boards with yarn are often used to present these ideas to students with visual impairments; however, the translation from the visual to the tactile domain results in a loss of information (Smith and Smothers, 2012). Although more complex solutions such as the Talking Tactile Tablet have been used in classrooms for testing pur-

poses, they rely solely on audio output, are not easily refreshable, and limit user interaction to a finite set of buttons (Landau et al., 2003).

In contrast to tactile technologies, haptic feedback mechanisms have been used for a variety of different applications since the 1960s, with initial research directed toward assisting people with visual impairments (Israr et al., 2014). For instance, the Optacon used input from an optical sensor to actuate an array of vibrating pins so that an individual could feel and interpret written text (Linvill and Bliss, 1966). Another device, the Tactile Television, converted camera images of basic shapes into an array of vibrating points (Collins, 1970). These initial studies on haptic assistive technology were a precursor to an influx of research in the field of surface haptics.

More recent developments in surface haptics have been consumer- and experience-driven, resulting in products developed for gaming and entertainment. For instance, the Marvel Avengers Vybe Haptic Gaming Pad primarily aims to enhance the gaming experience of neurotypical individuals (Israr et al., 2014). The Novint Falcon–a haptic device designed to replace a computer mouse–was developed as a gaming device, but has also been studied as an accessibility tool for users with visual

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impairments. The researchers used the Falcon's haptics as well as audio cues to display graphs and charts created in Microsoft Excel (Doush et al., 2010). This device enables the user to either actively interact with or passively perceive graphics and also demonstrates the potential of surface haptics to be used in assistive technologies. A similar device, the PHANToM, was used by Yu, Ramloll, and Brewster to present line graphs to both sighted users and users with visual impairments (Yu et al., 2001). Participants were tasked with exploring line graphs using the PHANToM force-feedback controller in order to find interesting features such as the maximum and minimum values and any points of intersection. While participants could generally discern the shape of line graphs, the perception was "often distorted and inaccurate due to the limitations of the force feedback device."

Electrostatics, a subfield of surface haptics, focuses on the development of haptic effects by applying voltages to a conductive surface in order to create friction on a user's finger. The researchers pioneered the development of electrostatic haptic technology when they created a tactile display by applying different voltages to an array of pins in order to produce texture (Strong and Troxel, 1970). Recently, researchers at Disney have continued this work by developing the TeslaTouch touchscreen device (Bau et al., 2010), which was analyzed as a tool to aid the visually impaired (Xu et al., 2011). This particular study included three participants who were totally blind and indicated that various representations of shapes have differing levels of effectiveness in conveying information. Specifically, participants were able to identify a solid shape at almost twice the rate of outline-only or solid-with-outline representations. The TeslaTouch system is novel but inherently infeasible for personal use, as it requires the user to be connected via a wrist strap and the device to be connected to a personal computer.

Other touchscreens have been explored as potential solutions to assist people with visual impairments in learning mathematical concepts. The researchers combined haptic and auditory modalities using a Series 1000 TouchSense Demonstrator device, and reported 66% success rates when sighted users were asked to navigate to specified Cartesian coordinates.[1] In a shape recognition task, users had difficulty discriminating shapes from one another, which the authors hypothesized was due to the variety of exploration methods utilized (Toennies et al., 2011). In a follow-up study with updated hardware (a Samsung Galaxy Tab 7.0) and users with visual impairments, the 66% navigation success rate was reproduced. However, when users were asked to identify the coordinates of given points, no combination of haptic/auditory grid and points yielded over 75% success (Gorlewicz et al., 2014). These studies have been foundational to the research presented in this paper, which aimed to extend the work of Gorlewicz et al. by investigating the role of exploration strategies in successful interpretation of haptic signals and by isolating the haptic sensory channel to optimize that modality prior to integrating auditory features.

Although previous research has used haptic technologies to address the unique needs of people who are visually impaired, a significant portion of the work published about tactile and haptic assistive devices does not include testing with individuals with visual impairments (Horton et al., 2016). We adopted a user-centered approach to the design of an electrostatic touchscreen system that provides graphical information to individuals with visual impairments. In addition, we conducted a usability study consisting of a haptic localization task in order to validate the efficacy and efficiency of the system and to determine patterns of user interactions with the touchscreen.

2. A user-centered design approach

The user-centered approach was dependent upon feedback in the form of interviews with assistive device experts as well as preliminary

tests with users with visual impairments. Fig. 1 depicts the iterative design process, which alternated these feedback sessions with hardware and software development.

2.1. First round of interviews

The first interviews focused on identifying the technological needs of students with visual impairments and their educators. We interviewed six individuals: a technology expert from the International Braille and Technology Center for the Blind (IBTC), the president of the Maryland chapter of the National Federation of the Blind (NFB), and the principal, vice-principal, and two elementary math teachers from the Maryland School for the Blind (MSB). The interviewee from the NFB is totally blind, while all other interviewees are sighted. Each of these sessions was conducted individually and at the interviewee's workplace. Each interviewee gave demonstrations of the technologies used in his or her classroom or office, and the expert from IBTC gave us a hands-on tour of the many technologies kept at the center. The first round of interviews was used to determine which hardware and software features are highly regarded among commercially available educational assistive devices, a goal which was made transparent to the interviewees.

The visit to the IBTC was aimed at understanding current trends in assistive technologies for people with visual impairments, as well as the primary challenges faced by users of these systems. The interview included questions such as "What categories of technologies are most widely used?" and "Which technologies receive the most criticism from educators and users? Why?" The responses revealed that although several devices had strong graphical precision, their general cost and bulkiness prevented them from being popular among the visually impaired community. Common concerns included: (1) the size and cost of high-tech devices, (2) cross-compatibility problems caused by the many types of assistive devices and their various operating systems, and (3) the dependency of devices on host computers, which renders them non-portable.

The interview with the NFB chapter president was similar to the previous interview, featuring questions about the fields of assistive technologies and education administration. The interviewee echoed the technology concerns raised by the IBTC expert, which strengthened the merit of these claims. In addition, she noted that in her time as an education administrator, teachers reported several challenges, such as finding adequate desk space for each student's own device and using devices designed without sighted instructors in mind. She encouraged us to ask about teachers' individual experiences with these concerns at the Maryland School for the Blind.

At the MSB, our interview questions differed from those asked previously, as they were directed at educators themselves, rather than technology and education experts. We asked educators about math curricula, the grade levels of various graphical mathematical skills, and the technologies they employed in their classrooms. Such questions included "How do you introduce your students to a new mathematical concept?" and "How are tests, homework, and classwork administered to students?" The teachers currently use Swell Touch Paper, Wikki Stix, and the Draftsman Tactile Drawing Board (see Fig. 2), but find that these tools provide neither immediate (speed of creating the first graphic) nor refreshable (ability and speed of creating subsequent graphics) interfaces. Graphs must be individually composed by hand or printed onto non-reusable paper, and are therefore not quickly adaptable to the students' learning needs. Despite their limitations, these low-tech media were preferred by teachers over higher-tech devices like the IVEO tablet, which reportedly took 1.5 h per graph to program. The educators identified refreshability, ease of programming, and intuitive display of information as essential qualities of assistive devices.

The educators also noted concerns about the design of educational assistive devices for classroom use. One of the essential missions of the MSB is to prepare students for integration into mainstream classrooms, but these classrooms have a number of limiting factors such as small

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[1] Although the hardware used in this study is mechanically-actuated as opposed to electrostatically controlled, the texture generated through both methods produces a vibrotactile effect.
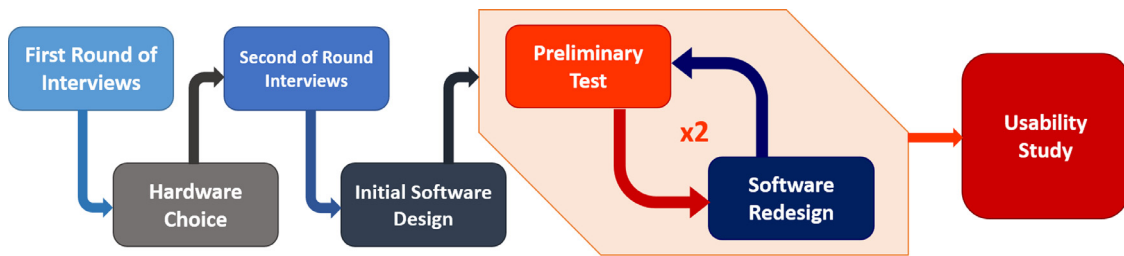
Fig. 1. *User-centered design process.* Illustration of methodological steps taken to design and test an electrostatic assistive system.
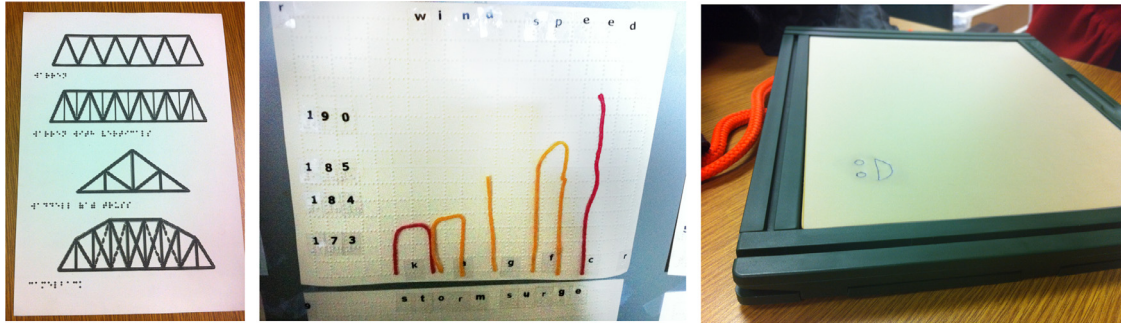

Fig. 2. *Traditional assistive technologies.* Images of (left) Swell Paper; (center) Wikki Stix, and (right) the Draftsman Tactile Drawing Board used at the Maryland School for the Blind (MSB).

desk sizes, lack of computers at workstations, and lack of one-on-one instruction for students with visual impairments. Therefore, they recommended that assistive devices be small, function independently of a host computer, run on battery power, and provide enough feedback for independent learning.

Finally, the educators detailed two opposing problems in the field of graphical accessibility devices. First, there is a need to transfer as much information as possible from the visual to the tactile domain to counteract the information loss inherent in the transfer process. Second, on the other hand, there is a need to simplify the tactile representation to avoid sensory overload. New technologies must be carefully developed to balance these two needs. One way to address the aforementioned information loss in tactile and haptic graphics is to provide additional multimodal information. The educators recommended using primarily auditory stimuli, supplemented by tactile and visual information.

From the first round of interviews, it became clear that an ideal system should be portable, freestanding, and affordable; have a powerful and commonly-used operating system; and have an intuitive, multimodal user interface. Based on a combination of information gathered from the interviews and a systematic literature review of assistive technology platforms, we chose to develop an electrostatic haptic touchscreen system. In Section 2.2, we describe the specifications of the hardware, which meet the aforementioned requirements.

2.2. Hardware choice – Tanvas electrostatic haptic touchscreen

The chosen device incorporates a haptic touchscreen developed by Tanvas.[2] The electrostatic touchscreen covers half of a 10.6 inch screen of a Microsoft Surface Pro 2 (Fig. 3) and has a resolution of 208 pixels per inch. The Tanvas overlay was constrained to a single point of contact (i.e. a user can only explore the touchscreen with a single finger at a time).

The system outputs a haptic effect once every four milliseconds. The intensity of the effect at any given time is controlled by an integer taking a value between zero (no haptic output strength) and 254 (maximum haptic output strength), with the value 255 reserved as an off state.
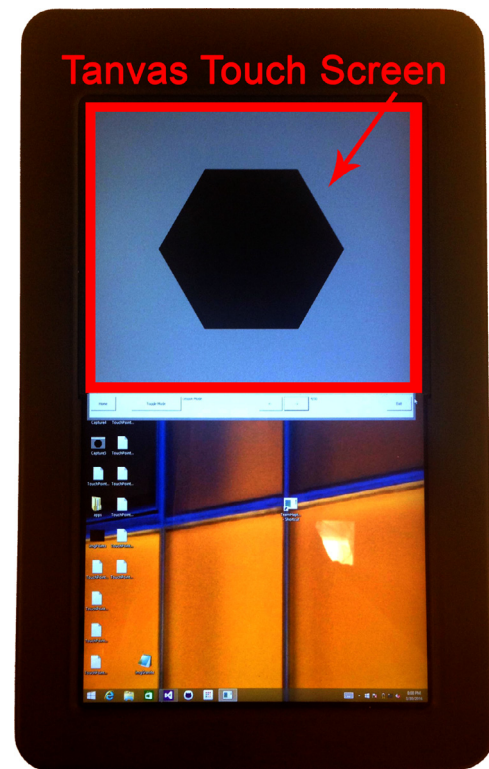

Fig. 3. *Tanvas electrostatic touchscreen.* Microsoft Surface Pro with Tanvas touchscreen overlay.

There are two types of haptic effects: (a) temporal haptic effects, which are generated by rapidly iterating through a fixed array of intensities such that the perceived effect varies over time and (b) spatial haptic effects, which are generated by mapping static integer values to each pixel on the screen such that the perceived effect varies by location. Both of these effects can be used to create textures that, once applied to a certain area of the screen, create the perception of a haptic object.

The electrostatic touchscreen has a 14 pixel touch resolution, so a haptic effect must be applied over at least a 14 pixel diameter to ensure that the effect will be perceived by the user. If an effect is placed over fewer than 14 pixels, a user is unlikely to perceive it.

Overall, this choice of hardware addressed a majority of the recommendations made by the experts during the first round of interviews. In particular, the Tanvas device is portable and freestanding due to its 7"×11.5" frame (which allows it to easily fit on any size desk) and it has a rechargeable battery which can last eight hours. The Surface Pro 2, running the Windows 8.1 operating system, can serve as a standalone computer or can be used in conjunction with most other devices, thereby addressing the educators' concerns about cross-device compatibility. The Surface itself provides audio and visual modalities, while the electrostatic overlay seamlessly integrates the haptic modality for a fully integrated user experience which suits users of all visual abilities. Although the electrostatic overlay is not yet commercially available, the estimated cost of producing such an overlay is only slightly higher than that of a standard, non-electrostatic touchscreen. However, the engineers of the screen expect the cost to decline over the course of the next few years due to improved manufacturing techniques and efficiency (G. Topel, personal communication, February 5, 2017). Following the selection of a hardware platform, additional interviews were conducted to inform the preliminary software design choices.

2.3. Second round of interviews

An expert-user interview was conducted with a Senior Staff Engineer at the National Library Service for the Blind and Physically Handicapped, who is totally blind. This individual was selected primarily because of his personal and professional experience with the use of assistive technologies. He is also a frequent guest in special education courses at the University of Maryland, lecturing about the academic technological needs of students with visual impairments. The goal of this interview was to determine the necessary and desired software features and applications for the device, a goal which was again made transparent to the interviewee. The interviewee suggested providing orientation and positional information and maintaining consistency in the presentation of haptic features. For instance, the edges of the touchscreen provide constant spatial orientation. The interviewee also suggested that important UI features, such as navigational buttons, remain in a fixed location on the screen to promote ease of user navigation.

The interviewee reported his personal experience in college-level math classes, in which the greatest challenges arose not from the difficulty of the mathematical concepts but from the increasingly complex visuals associated with them. In particular, the lack of refreshable devices meant that in order to access a tactile version of a graph shown in class, he had to wait multiple days and pay a peer to draw it on embossed paper. While he easily understood the basic components which make up graphs, the combination of graphical components into a cohesive image is perceptually challenging. The interviewee's personal difficulties with understanding graph-based concepts informed our decision to focus our software development and preliminary test on the various subcomponents of graphs.

2.4. Initial software design

The initial software design had three goals: (1) to promote ease of programming and administering lessons for a sighted teacher, (2) to investigate static UI features that provide spatial orientation for the user, and (3) to create the software for the first preliminary test.

In order to meet the needs of the educators at MSB, we designed a system for teaching lessons in the format of a haptic slideshow, in which each slide contained haptic images. This system allowed teachers to navigate through slides one at a time via navigational buttons at the user's own pace. Additionally, to address the teachers' frustrations with having to painstakingly program lessons into devices, the software was

designed to support the rapid creation of commonly used mathematical objects like circles, lines, and rectangles.

Secondly, we implemented a feature to help users with visual impairments find static UI elements. Specifically, we created a single haptic circle, named the Home Button, to serve as a test UI button and to provide spatial orientation information. When the user held their finger on the Home Button, the device would beep three times before the button was activated. Based upon the assumption that spatial orientation information is needed most at the position furthest from all other points of reference (such as corners and edges), we initially placed the button in the center of the screen.

Finally, in preparation for the first preliminary test, we embedded new haptic objects into the slideshow, with a focus on providing multiple variants in the representations of these objects in order to determine user preference. Specifically, we added objects that comprise components of a graph such as dots, circles and regular polygons, lines of varying thicknesses, and graph axes. Shapes had two styles of haptic representation: (1) a haptic effect within their whole area, and (2) a haptic effect only on their outline. In addition to different shape representations, we implemented three different textures. These included: (1) Granite, a temporal effect Tanvas designed to feel like granite, (2) PeakAndGradient, a temporal effect we designed to create peaks and valleys in intensity, and (3) HexHole, a temporal effect we designed to feel like a mesh of strong intensities with regular gaps. The three textures were motivated by existing texture generation techniques in the original Tanvas system, as well as the need for preliminary textures in order to gain initial user feedback as to which textures are desirable.

2.5. Preliminary test 1

A first preliminary test was conducted with an adult male who is totally blind, holds a Ph.D. in Mathematics, and served as treasurer of the Science and Engineering Division of the NFB. Throughout the test, the participant was asked to first provide his own opinion of each haptic feature and then critique the feature based on his expert knowledge of device preferences of members of the blind community. Based on the participant's feedback, parallel prototypes for a variety of software features were developed.

The test took place in a small classroom in the Gemstone Honors Program suite at the University of Maryland. The user and the test administrator were seated across from one another, with two additional researchers taking notes and timing from the other table. The user was presented with ten slides, each containing a single shape rendered with the Granite texture, and was asked to identify the shape. A circle, triangle, square, hexagon, and octagon were shown one at a time in a pseudorandom order using the filled representation and then again in a different pseudorandom order using the outlined representation. While he performed equally well at identifying filled and outlined shapes, he reported that the outlined shapes were much more difficult to identify, and attributed his success to having gained experience from the filled shapes. The circles were difficult to identify due to their lack of distinguishing angles, while the triangles were easiest to identify due to their acute angles. Each additional side made the shape harder to correctly identify. For example, when presented with an octagon, the user believed it to be a circle, and maintained that the two were indiscernible even upon correction.

The user was then shown three slides, each consisting of two filled squares of different textures. He was asked to describe the difference between each pair of textures and to identify which he preferred. In analyzing the three textures shown, the user had no consistent preference and insisted that all three were too "weak" for him to feel well.

To determine the preferred thickness of a line, we created a single slide with eight parallel vertical lines of decreasing thickness. The user could detect only the five thickest lines, which ranged from 38 pixels to 10 pixels in thickness. He reported that 38 and 30 pixels were far too

thick to represent lines, and his preferred lines were 14 and 10 pixels thick.

Finally, the user freely discussed design choices and recommendations. His primary feedback was the need for multitouch capabilities (multiple fingers in contact with the screen simultaneously), which would allow him to use one finger as a point of reference and another for exploration. However, the Tanvas device was limited to a single point of contact at that time. To help correct for this, he suggested points of reference such as menu buttons, which were also mentioned in our expert-user interview. After being shown the Home Button, he believed the bottom and the corners of the screen to be the best place for such UI buttons, and appreciated the auditory cues that it produced when touched. He also believed that auditory information would greatly strengthen the effectiveness of the device, as being told what shape he was feeling made it much easier to trace it. When asked if audio should be incorporated as a primary or secondary means of information transfer, he suggested to initially test only the haptic effects. He reasoned that the superiority of multimodal devices is well-established, so it is best to optimize the haptics independently in order to ensure that the strength of the device can be attributed to the haptics.

2.6. Software redesign 1

The first software redesign was motivated by three primary recommendations: (1) to create stronger haptic textures, (2) to make the corners of shapes more pronounced, and (3) to determine the optimal thickness of a haptic line.

In order to create the strongest possible texture, the upper limits of the device's frequency and amplitude capabilities were analyzed. It is known that the optimal frequency for vibration detection falls between 200 and 300 Hz (Mortimer et al., 2007). The frequency output of the Tanvas device was then maximized to 125 Hz by using only two intensity values: 0 and 254. These intensities were selected to maximize the amplitude of the haptic signal, so we named the texture MaxAmp.

The participant from the first preliminary test cited the corners of shapes as their key distinguishable features. As a result, two approaches were defined to improve the identifiability of corners, but were ultimately not used. The first approach involved strengthening the haptic effect near corners by applying the MaxAmp texture to the vertices of shapes and the Granite texture to the rest of the shape. However, we did not include this haptic method in the second preliminary test because the implementation of a corner texture required too large a surface area for each corner, such that this texture eclipsed the original shape. For the second approach, auditory feedback in the form of a clicking noise was produced when the user's finger crossed over a vertex. Although a potentially successful strategy for improving vertex identification, the auditory feedback method was not included in further testing because of the participant's warning about audio eclipsing haptics as the primary modality.

Finally, a smaller range of line thicknesses was tested based on the responses of the first preliminary participant. A decision was made to use the three thicknesses that he deemed neither too thick nor too thin: 20, 14, and 10 pixels. In addition, lines that were 18, 16, and 12 pixels thick were included to allow for greater specificity.

2.7. Preliminary test 2

We conducted a second round of testing with a Senior Staff Engineer from the National Library for the Blind and Physically Handicapped, who was the expert-user from the second round of interviews (Section 2.3). We hoped to determine whether our software re-design had fulfilled his initial recommendations. The second preliminary test protocol was similar to the first, but included the new MaxAmp texture and two new shapes (the pentagon and heptagon), and featured the aforementioned refined range of line thicknesses. In the shape identification portion, shapes with the most sides were again indiscernible

from circles, triangles were again the easiest to identify, and the participant strongly preferred filled over outlined shapes.

The side-by-side comparisons of textured squares now featured every pairwise combination of the four available textures. Of the textures presented, Granite and MaxAmp were preferred over PeakAndGradient and HexHole due to a higher perceived intensity. However, the participant noted that he would prefer an even "stronger" texture.

The refined set of vertical line thicknesses was presented in order to determine which was ideal for haptically portraying lines. The participant's preferred thickness was 20 pixels, which is slightly thicker than the preferences of the first preliminary participant. Based on the expert recommendations, a second round of design changes was made.

2.8. Software redesign 2

Based on the continued superiority of filled shapes, outlined shapes were entirely discarded. The canonical line thickness was set at 20 pixels, due to both preliminary test participants recognizing it as an adequate thickness, and one participant being unable to perceive the thinner lines preferred by the other. When creating more complex graphical elements such as axes and function curves, we maintained this line thickness. While the development of haptic representations of these other graphical elements continued, we made the decision to focus solely on the users' ability to locate small haptic circles on the device for the purposes of an initial usability study.

The haptic effects shown in the preliminary tests were quite limited in comparison to the full range of software features developed. The aforementioned line thickness was used to determine the optimal length of a tick mark on an axis, which was in turn used to determine the optimal diameter of a dot which would be placed on a coordinate system. We chose a diameter of 120 pixels for a haptic dot and selected to fill these haptics dots with the MaxAmp texture based on the feedback from both participants. The decision to limit the study to single-texture haptic dots allowed for a more thorough exploration of the general usability of the haptic device and the optimal locations for static user interface features.

3. Usability study

To better understand how users experience the electrostatic touchscreen system, we conducted a usability study consisting of a number of trials of a simple localization task using only the haptic modality. The primary metrics studied were accuracy (rate of correctness in responses) and efficiency (time between initial contact with the device and verbal response). We developed a series of specific aims in order to verify and evaluate the effectiveness of our design choices at accomplishing our previously stated goals. The aims of the study were: (1) to determine whether accuracy changed across trials, (2) to determine whether efficiency changed across trials, (3) to analyze the strategies by which participants explored the screen, and (4) to determine whether the location of each dot on the screen significantly affected accuracy.

3.1. Participants

Participants were recruited from the National Federation of the Blind of Maryland and the Maryland School for the Blind. The inclusion criteria were: minimum age of eight years old, visual impairment of at least legal blindness as defined by the World Health Organization, and absence of neurological or physical disabilities beyond blindness. The demographics and visual impairment of all participants are summarized in Table 1. All participants included in this study were also required to pass three cognitive tasks that tested their ability to: (1) verbally count from zero to ten, (2) differentiate a straight line from a sinusoidal curve, and (3) distinguish dots from dashes. All adult participants gave informed consent, and a parent or legal guardian of each child gave his/her in-

Table 1

Demographics of participants. Visual impairment levels were categorized into S - Severe Visual Impairment (20/200 - 20/400), B - Blindness (20/400 - 20/1200), and T - Total Blindness (No Light Perception).

	Participant ID											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Gender	M	F	F	M	M	F	M	M	F	F	M	F
Age	17	16	20	9	14	12	10	11	9	40	15	50
Visual Impairment Level	B	B	S	B	B	S	B	B	B	B	T	T

Table 2

Average *quintile accuracy.* Average accuracies across quintiles including all participants (center) and only including those who mastered the task (right).

Quintile Number	Avg Accuracy (All)	Avg Accuracy (Mastery)
1	0.775	0.573
2	0.733	0.736
3	0.963	0.959
4	0.829	0.886
5	0.967	1.000

formed consent based on the procedures approved by the University of Maryland's Institutional Review Board (IRB).

3.2. Methods

Each participant was blindfolded to ensure that visual stimuli did not affect performance, a measure which is often employed in user testing within the blind community (Maryland School for the Blind, personal communication, November 13, 2013). The protocol consisted of 30 slides displayed on the device, each with a single haptic dot measuring 120 pixels in diameter and located at one of 30 evenly-spread, predetermined locations on the screen. The participants were asked to locate the dot on the screen with their finger and verbally affirm that they had found it. The participant was given 45 s per slide to complete the task before being prompted for a response or allowed to give up. The response accuracy and the time elapsed from initial contact with the screen to verbal response were recorded with a video camera. If at any point, five consecutive dots were correctly identified by the user, the test concluded, as the participant was deemed to have mastered the task. Video analysis was used to confirm response and time, as well as to analyze the strategy used to explore the screen.

3.3. Results and discussion

Of the 116 total trials completed, participants correctly located the dot with an accuracy rate of 69.83% and an average time of 15.34 s. 11 of the 12 participants correctly identified five dots in a row within the 30 dots allotted, with the 12th choosing to withdraw from the study after 25 trials.

3.3.1. Specific aim 1: accuracy analysis

In order to determine whether accuracy rate changed across trials, each participant's trials were partitioned into quintiles (five even partitions, with extra trials in the earlier quintiles in the case of unevenness). The quintiles adjust for the difference in the number of completed trials across participants. The overall accuracy rate for each quintile was determined by averaging the quintile accuracy across participants. Additionally, the single participant who did not master the task within 30 trials was removed to find the average quintile accuracy across participants who gained mastery of the task. The quintile accuracy data can be found in Table 2.

A linear regression analysis of the average accuracies for every participant resulted in an R^2 value of 0.500, as shown in the top graph in Fig. 4. A linear regression analysis of the average accuracies for only
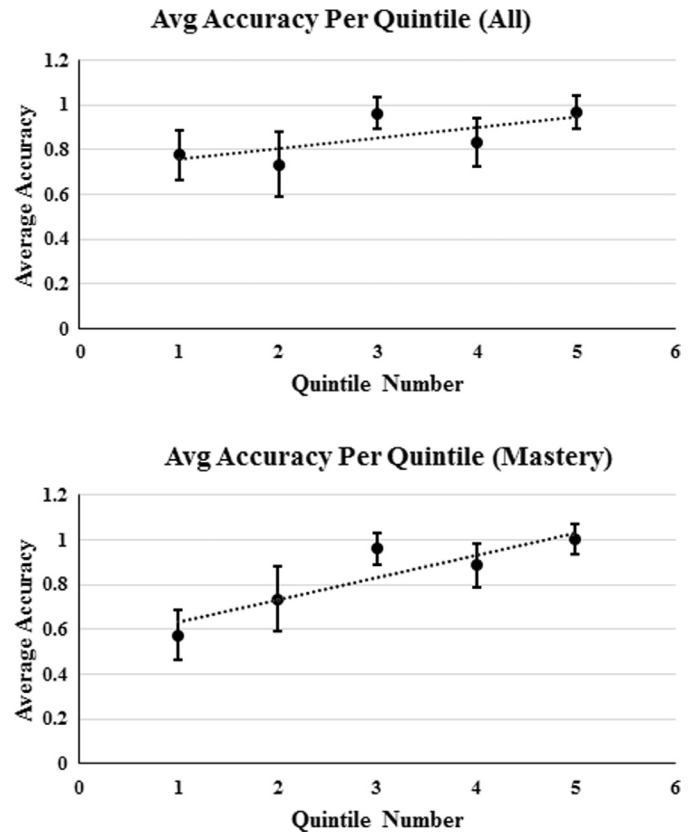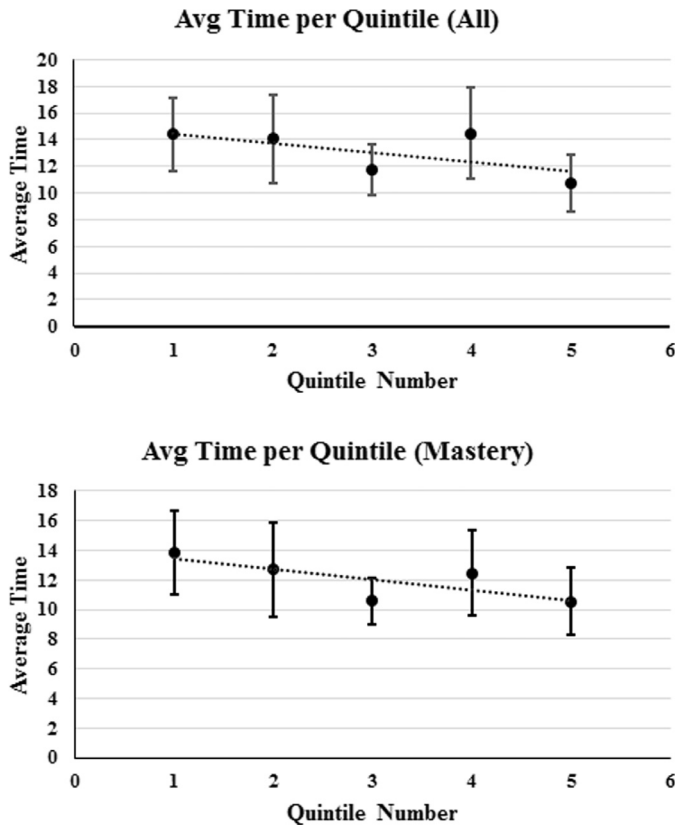

Fig. 4. *Linear regression of quintile accuracy.* Linear regression of average accuracies across quintiles including all participants obtained an R^2 value of 0.4048 (top) and when only including those who mastered the task obtained an R^2 value of 0.5734 (bottom). The error bars represent the standard error of the mean for each quintile.

those who mastered the task resulted in an R^2 value of 0.816 and is shown in the bottom graph in Fig. 4.

A t-test of the slope of the regression line was used to determine if there is a significant relationship (alpha = 0.05) between quintile and accuracy. We obtained a p-value of 0.18, indicating no significant relationship between trial number quintiles and average accuracy. However, upon removing the single participant who did not correctly identify 5 dots in a row, we obtained a p-value of 0.04, indicating that there is indeed a significant relationship between trial number quintiles and the accuracy of response for the participants who gained mastery of the device within 30 trials.

Of the 12 participants, 11 gained mastery of the simple haptic tasks within 30 trials, with the average participant only needing 8.27 trials to do so. In addition, these 11 who showed a basic understanding of the haptic representations also exhibited a learning curve, as evidenced by the p-value of 0.04. These results indicate that most people with visual impairments can perform simple tasks using an electrostatic touchscreen and can rapidly improve in their performance of the task.

Table 3

Average quintile efficiency. Average efficiencies across quintiles including all participants (center) and only including those who mastered the task (right).

Quintile Number	Avg Time in seconds (All)	Avg Time in seconds (Mastery)
1	14.425	13.845
2	14.067	12.727
3	11.725	10.591
4	14.467	12.455
5	10.733	10.545

Avg Time per Quintile (All)

Avg Time per Quintile (Mastery)

Fig. 5. *Linear regression of quintile efficiency.* Linear regression of average efficiencies across quintiles including all participants obtained an R^2 value of 0.4048 (top) and only including those who mastered the task obtained an R^2 value of 0.8158 (bottom). The error bars represent the standard error of the mean for each quintile.

3.3.2. Specific aim 2: efficiency

In order to determine whether efficiency changed across trials, each participant's trials were again partitioned into quintiles. The overall efficiency rate for each quintile was calculated by averaging the quintile efficiency across participants. The quintile efficiency data can be found in Table 3.

Linear regression analysis of the efficiency for every participant resulted in an R^2 value of 0.405, as shown in the top graph in Fig. 5. Linear regression analysis of the average time for those who mastered the task resulted in an R^2 value of 0.573 as shown in Fig. 5.

A t-test of the slope of the regression line was used to determine if there is a significant relationship (alpha = 0.05) between quintile and efficiency. We obtained a p-value of 0.25, indicating no significant relationship. With the same single participant removed, the p-value changed to 0.14, still indicating no significant relationship.

The linear regression showed no significant improvement in efficiency, however the lack of improvement does not affect the general usability of the system, which is primarily designed to transfer graphical information to users accurately rather than quickly. Therefore, improved efficiency is less important than improved accuracy, especially in light of the extended time which students with accommodations for their
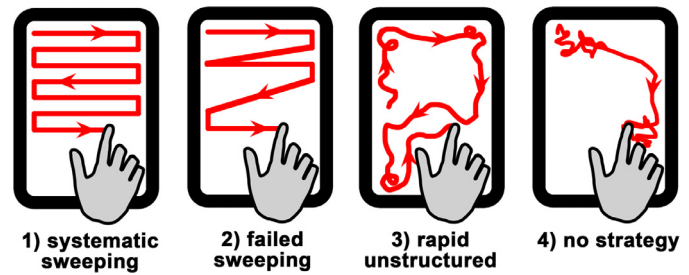

Fig. 6. *Exploration strategies.* Visual depictions of four exploration strategies, from systematic back and forth sweeping to no discernable strategy.

visual impairments are typically afforded (American Foundation for the Blind, 2016).

3.3.3. Specific aim 3: strategy analysis

In order to analyze participants' exploration of the electrostatic touchscreen, we first labeled each participant with one of four strategies: (1) systematic sweeping motions, (2) attempted sweeping motions with significant gaps, (3) rapid unstructured screen exploration with a focus on corners, and (4) no discernible strategy (Fig. 6). The strategies were defined via the process of iterative coding, in which videos of the participants' movements were first grouped by general visual similarity, then group names were given to each cluster, and finally each video was watched again to verify the most accurate categorization. The average accuracy rate–ratio of correctly located dots to total trials–for each strategy can be found in Table 4. Due to the limited number of participants in each category, these results have been limited to descriptive statistics.

In examining the four strategies and their respective accuracy rates, we can see that 50% of participants intuitively used a strategy which yielded an accuracy rate of over 90%, which we deem highly successful. The systematic sweeping strategy was expected to be successful due its methodical nature, but rapid unstructured screen exploration with a focus on corners was surprisingly effective (100% accuracy across four participants). We attribute the success of this strategy to three factors: (1) locating the corners at the beginning of every trial allows the user to spatially reorient themselves and ensure coverage of the full length and width of the screen, (2) rapid motion results in higher coverage of the screen in a shorter period of time when compared to slower motion, and (3) rapid motion enhances the perception of friction. Among participants who did not perform one of the two highly successful strategies, 66% attempted and failed to execute the systematic sweeping strategy. Given that the intuition of using a systematic strategy is not lacking, additional feedback from the device informing participants if they have overlooked parts of the screen is likely to improve the execution of this strategy. Additionally, for users who do not intuitively use one of the highly effective strategies, we believe that these strategies can be taught via auditory output from the device or the assistance of an instructor, though this claim requires additional research.

3.3.4. Specific aim 4: location-based accuracy analysis

In order to determine whether the location of the dot on the screen affected the cross-participant accuracy rate for that dot, we calculated the average accuracy rate for each slide which was completed by at least five participants. Again, the analysis is limited to descriptive statistics. As seen in Fig. 7, the accuracy rates for dots in the corners of the screen tended to be higher than those for dots nearer to the center of the screen. Additionally, 11 of the 12 participants had higher average accuracy rates on those three corner dots than they did on all dots. While the results do not necessarily indicate poor accuracy in the middle of the screen, they do indicate relatively high accuracy on the corners (over 80%). These findings corroborate the assertions of our two preliminary participants,

Table 4

Average accuracy for exploration strategy. Different strategies used by participants (left), the number of people who used each strategy (center), and the average accuracy rate for each strategy (right).

Strategy	Number of Participants	Average Accuracy Rate
Systematic Sweeping	2	0.917
Failed at Systematically Sweeping	4	0.739
Rapid Unstructured Screen Exploration	4	1.000
No Discernible Strategy	2	0.735
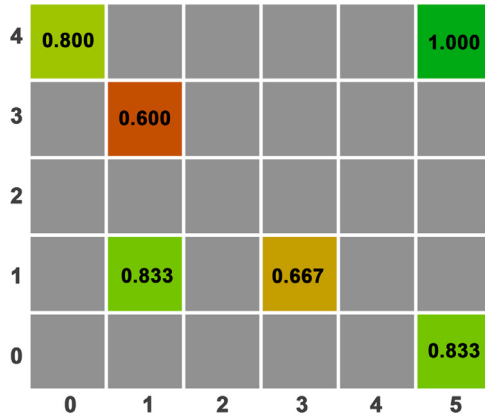
Fig. 7. *Accuracy heatmap*. Heatmap of accuracy rates for screen locations completed by at least five participants.

who stated that the corners of the screen were the best for static UI elements such as a home or menu button.

4. Limitations

There are several limitations regarding the user-centered design process, the usability study, and the hardware itself. In the second round of interviews (Section 2.3) and in each of the preliminary tests (Sections 2.5 and 2.7), we obtained information from only one participant. However, each participant, through his or her personal experiences, combined with an expertise in the field of education technology, offers valuable insight on the needs of the broader population. The usability study was similarly limited due to a small population of potential participants. Although a larger number of participants would strengthen the validity of our results, the sample size of 12 participants was sufficient to produce statistically significant findings regarding the improvement of users' ability to accurately locate haptic dots. Additionally, previous research in usability testing has shown that five users can sufficiently identify nearly 85% of the usability concerns of a device (Faulkner, 2003; Nielsen and Landauer, 1993).

At the time of the study, the hardware was limited to a single point of contact. However, this limitation was controlled across all participants, and participants did not have difficulty following the instruction to use only one finger. Once the field of electrostatic touchscreens progresses to allow reliable multitouch haptics, further research will be required to extend the findings of our study to a multitouch system.

5. Conclusion and future directions

Prior research about haptic accessibility devices for people with visual impairments frequently does not take a user-centered approach in the investigation of desired features and functionalities or the testing process itself. This study differs from and improves upon the existing literature in the following ways: (1) the device in this study is a portable, standalone system with a powerful operating system, (2) we received feedback from a larger and more varied group of users, all of whom have profound visual impairments, and (3) we implemented an itera-

tive, user-centered design process in order to develop an assistive device which is optimized for people with visual impairments. The improvement of the participants' accuracy in locating haptic dots demonstrates the usability of the device, and the ability of the participants to develop effective screen exploration strategies indicates that the device is intuitive for users. Finally, the device itself meets the desired accessibility needs laid out by previous studies, experts, and educators in the field.

Moving forward, three future directions could be pursued based on the findings of this work. The first is to test the usability of the device in regards to increasingly complex graphical concepts. To that end, haptic representations of lines, axes, and simple plots in Cartesian space could be developed and tested. The second direction is to integrate multimodal output in order to create a more complete system which can be used independently by people with visual impairments. Specifically, we could determine whether auditory feedback can be used to teach effective strategies to users or to correct behaviors such as the failed systematic sweeping motion. The third direction is to enable multiple points of contact with the touchscreen, which was universally requested by the MSB educators and preliminary test participants. With improvements to the hardware and firmware to enable multitouch, future work is required to determine the impact of improved spatial awareness on performance of complex haptic tasks.

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