Non-visual Perception of Lines on a Multimodal Touchscreen Tablet

JENNIFER L. TENNISON and JENNA L. GORLEWICZ, Saint Louis University

While text-to-speech software has largely made textual information accessible in the digital space, analogous access to graphics still remains an unsolved problem. Because of their portability and ubiquity, several studies have alluded to touchscreens as a potential platform for such access, yet there is still a gap in our understanding of multimodal information transfer in the context of graphics. The current research demonstrates feasibility for following lines, a fundamental graphical concept, via vibrations and sounds on commercial touchscreens. Two studies were run with 21 blind and visually impaired participants ($N = 12$; $N = 9$). The first study examined the presentation of straight, linear lines using a multitude of line representations, such as vibration-only, auditory-only, vibration lines with auditory borders, and auditory lines with vibration borders. The results of this study demonstrated that both auditory and vibratory bordered lines were optimal for precise tracing, although both vibration- and auditory-only lines were also sufficient for following, with minimal deviations. The second study examined the presentation of curving, non-linear lines. Conditions differed on the number of auditory reference points presented at the inflection and deflection points. Participants showed minimal deviation from the lines during tracing, performing nearly equally in both 1- and 3-point conditions. From these studies, we demonstrate that line following via multimodal feedback is possible on touchscreens, and we present guidelines for the presentation of such non-visual graphical concepts.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; **User studies**; **Touch screens**; **Interaction techniques**; **Accessibility**; *Auditory feedback*; *Gestural input*; Accessibility design and evaluation methods;

Additional Key Words and Phrases: Haptics, touchscreen, perception, HCI

ACM Reference format:
Jennifer L. Tennison and Jenna L. Gorlewicz. 2019. Non-visual Perception of Lines on a Multimodal Touchscreen Tablet. *ACM Trans. Appl. Percept.* 16, 1, Article 6 (February 2019), 19 pages.
https://doi.org/10.1145/3301415

1 INTRODUCTION

Early studies illustrate the potential of touchscreens to be accessible interfaces via the use of multiple sensors (e.g., GPS), speech input, and text-to-speech functions that allow blind and visually impaired (BVI) users to navigate, collaborate, and explore the digital space [17, 19]. However, there remains a gap in our understanding of multimodal information transfer via different constituent inputs (i.e., as vibration and sound) [15, 17, 19, 31]. While textual information has largely been made accessible in the digital space via text-to-speech software, analogous access to graphics remains a largely unsolved problem, with alt tags and textual descriptions being among the most common methods of addressing graphics [6]. Lack of access to graphical material, however, is more than a mere frustration. Digital accessibility represents one of the biggest challenges to the independence and

This work is supported by the National Science Foundation, under Grants No. 1549009 and No. 1644538.
Authors' addresses: J. Tennison and J. Gorlewicz, Aerospace and Mechanical Engineering Department, Parks College of Engineering, Saint Louis University, 3450 Lindell Blvd., St. Louis, Missouri, 63103, USA; J. Gorlewicz is also President and Co-Founder of JLG Innovations, LLC.

1544-3558/2019/02-ART6 $15.00
https://doi.org/10.1145/3301415

productivity of individuals with BVI and has had significant detrimental effects on the educational, vocational, and social prospects for this demographic [2, 29].

In this work, we explore how to render and explore one of the fundamental building blocks of graphics—lines—via multimodal feedback on touchscreens. Non-visual line following and recognition on touchscreens is a barrier to graphic exploration of digital tactile graphics. A touchscreen's surface is smooth, providing no cutaneous cues informing perceived attributes such as line orientation, width, and depth to signify being on or off a line [19, 30]. This makes it challenging to identify or follow presented pathways. Lines form the basis from which more complicated visual representations and spatial information organizers are created, making it imperative that we understand how the impression of lines can be best facilitated on touchscreens.

In this work, we address this barrier in the context of BVI touchscreen users, exploring line profiles that promote effective following and replication of both linear and non-linear trajectories using auditory and vibratory feedback from touchscreens. We first provide a brief literature review in Section 1.1, presenting both opportunities and challenges of the touchscreen platform as a multimodal, graphic display before presenting two studies that explore line following and perception. These studies are introduced in Section 2 and are detailed in subsequent sections.

1.1 State of Research

Current research regarding touchscreens as multimodal graphics displays has made great strides building off of research into path-finding [31], interface creation [25], communication [28], as well as more specific, graphics related research [13, 15, 16]. Research on force-feedback devices has already shown promise in graphical content understanding for individuals with BVI. Studies using a combination of haptic and audio feedback have shown the advantages of leveraging multimodal cues. Through this research, we know that the use of discrete markers (such as tick marks, bumps, and borders), auditory cues (e.g., pitch, volume), and varying the texture (in the case of multiple lines) further promotes understanding of the graphic (e.g., References [1, 7, 32, 36–38]). While the findings from this line of research inform touchscreen-based research, the feedback provided from force-feedback devices is different than the vibratory feedback provided from touchscreens. As opposed to kinesthetic cues from force feedback, which enable the user to move their entire arm and hand for exploration, the tactile feedback from touchscreens uses vibrations on a single finger tip. Further, much of the previous work involved device-mediated interactions, as opposed to direct interaction with a user's fingertip. These differences result in new challenges in reliably rendering graphics and exploring them non-visually on touchscreen platforms. These challenges can be categorized into the following areas: (1) Replication of physical cues and bio-physical limitations and (2) cognitive handling of information.

1.1.1 Replication of Physical Cues and Bio-phystical Limitations. A fundamental challenge exists in the replication of important physical cues from tangible objects that cannot easily be represented on commercially available touchscreens [19]. When exploring objects in the physical space, individuals have the added benefit of being able to judge an object by size and texture [20, 21]. When exploring raised line graphics, individuals can judge the direction of continuous line segments and easily differentiate points that are very close together due to the resolution of the finger pad and advantageous hand gestures [19]. On a touchscreen, however, triggering haptic feedback vibrates the entirety of the screen, which means no localization of feedback. Furthermore, only a single pixel under the finger pad (often the calculated center of all contact points) triggers vibratory effects on the screen. This one pixel determines what feedback is given at any point. Contrast this with the ability to feel multiple distinct features on the finger pad on embossed print media. Thus, the perceptual cues and sensory feedback provided by touchcreens is fundamentally different than print tactile graphics, leading to new inquiries on how to render information that promotes effective, non-visual interpretation.

To understand physical objects and raised line drawings, individuals can use strategies such as expanding the haptic field of exploration (using the entire arm instead of just one finger) [5, 8] and sweeping (of the hand/fingers) over a small surface to create a better understanding of the overall shape and its texture [22, 33, 34]. Along with expanding the haptic field, leading an individual's finger to trace (for instance, a raised line drawing) is also a beneficial strategy that encourages understanding of what is being felt [26]. While we can leverage strategies such as the latter to aid in touchscreen exploration of graphics, we need to better understand the affordances of multimodal cues on touchscreens in the context of graphics.

Because they are smooth, flat surfaces, commercially available touchscreens are not capable of conveying the physical characteristics described above, making graphic identification on touchscreen surfaces challenging. Nonetheless, incorporating multimodal cues (e.g., vibration, audio, spatial) is hypothesized to assist non-visual navigation and interaction with a touchscreen display [20]. For instance, multimodal cues can be used to indicate important areas of the figure on the touchscreen [19]. This can be put into practice by simply using a different auditory cue for key points on shapes or lines (i.e., inflection and deflection points). This echoes previous work done by Goncu and Marriott [15] as they facilitate shape recognition on a touchscreen, by providing stronger vibrations or different sounds at vertex points. Doing so may help the user obtain a mental representation of important graphical features, such as line direction.

An additional perceptual challenge for touchscreen-induced haptic feedback is that vibrations stimulate the entire fingertip, making finely detailed information that would be easily discernible physically and visually quite difficult to distinguish on a smooth tablet. Moreover, constant vibration can lead to sensory fatigue, limiting a user's ability to perceive different vibrations over time [3]. In this work, we investigate whether these limitations are barriers to interpreting and tracing line profiles using multimodal feedback on touchscreens.

1.1.2 Cognitive Handling of Information. Interpreting graphics is also cognitively demanding when performed without visual assistance. Although non-visual graphics interpretation is possible, it can take users much longer to understand and interpret visual information as conveyed by vibrations on a touchscreen [13, 15]. However, there is evidence that perceptual learning that normally occurs in vision may also occur in touch, as more experience with haptic exploration can lead to fewer judgment mistakes when identifying ambiguous tactile images [8].

In addition to the above challenges, there are limitations to the resolution and perceptual processing of vibrations. While touch is an integral part of how we explore and manipulate our environment [23, 27], it cannot replace vision entirely. Visual and haptic perception differ in a number of ways including spatial localization, temporal integration, and vulnerability to systematic distortion [19]. Those who design graphics in the haptic space are challenged by the limitations of spatial bandwidth and temporal processing capabilities, along with the difficulties introduced by the active nature of touch encoding [19].

Because vision, hearing, and touch share spatial commonalities, however, each can substitute for another to varying extents. Research done by Giudice and colleagues has demonstrated that spatial learning between sighted and BVI individuals is similar across modalities when the necessary information is provided. Functional equivalence has been shown for vision and verbal descriptions [9, 10], vision and spatialized audio [14], and vision and touch [11, 12]. In addition, a recent neuroscientific study has demonstrated that sighted and BVI individuals utilize the same brain regions for visual and haptic processing of environments. This may indicate that these modalities can be processed as amodal spatial constructs in the brain [35].

Vibratory feedback is currently the state of the art in touchscreens. Recent studies have shown that vibrations can relay semantic information and have promise in the non-visual interpretation of graphics (such as bar charts and spatial maps) [13, 16, 31]. In this work, we build upon current research that suggests multimodal feedback (haptic and audio) is beneficial for graphical content understanding (e.g., [19]). This work explores line following on touchscreens—a fundamental problem to exploring more complex graphics. Specifically, we investigate how vibrating lines, both linear and non-linear, are perceived with the inclusion of auditory feedback for important features.

2 CURRENT STUDIES

This work builds upon prior research that has suggested the potential of vibratory and auditory feedback but that has not yet been validated with dedicated user studies specifically focused on promoting line following on touchscreens. We now present a summary of our research questions, hypotheses, and user studies that support this work.

2.1 Research Questions

2.1.1 Study 1—Linear Line Perception. The goal of the first study was to determine representations of lines that promote efficient (i.e., least amount of time per task) and effective (i.e., minimum deviation from line) line following and perception via vibratory and auditory feedback on touchscreens among users with BVI. This study specifically examined line following as well as software- and user-side strategies that may improve the task.

Specifically, we proposed two key questions: (1) Can individuals with BVI accurately follow lines using only vibratory and/or auditory feedback on touchscreens with a finger? (2) What is the optimal feedback type to represent lines on touchscreens as evaluated by accurate tracing, re-creation, and user preference? To answer these questions, we conducted a study exploring six line representations (Vibrating Solid; Vibrating Dashed; Auditory Solid; Auditory Dashed; Auditory Border/Vibrating Midline; and Vibrating Border/Auditory Midline), each in five profiles (horizontal, vertical, left diagonal, right diagonal, straight with obstacle), as discussed in Section 4 and shown in Figure 2.

We hypothesized that vibrations alone can facilitate accurate, non-visual line perception on touchscreens for users with BVI. We also hypothesized that bordered line representations were optimal for finer tracing and promote less deviation (both in amount and distance) from the line.

2.1.2 Study 2—Non-linear Line Perception. The second study was constructed from one of the main challenges of the first study—perception of lines with unexpected deviations (e.g., points and curves) on touchscreens with a finger. The goal of this second study was to determine the minimum amount of information a user needed to perceive and follow non-linear lines on a touchscreen. This was done by including auditory key points that mark important features of the curved line, namely inflection and deflection points of each curve.

In this second study, two conditions were presented to participants: (1) one auditory point at each inflection and deflection point of a curve, signaled with the same pitch and (2) three auditory points at each inflection and deflection point, signaled with relative pitch. This methodology is further explained in Section 4. We investigated two key questions: (1) Is the auditory-point method of expressing curved lines sufficient for individuals with BVI to follow the curves in a timely fashion (e.g., under 3min)? (2) Do participants deviate more from line paths in the 1-point condition over the relative pitch, 3-point condition?

We hypothesized that the single-point condition would be sufficient to satisfactorily address both questions, and that more information is not necessary to facilitate timely line following with minimal deviation from the line.

These two studies inform our understanding of the possibilities and limitations of rendering lines via multi-modal feedback on touchscreens. Answers to these inquiries provide a better understanding of how users perform line following tasks non-visually and provide guidelines from which more complex graphical entities can be represented. We discuss our findings in the context of guidelines in Section 5.

2.2 Methods

Both studies made use of a 10.5in., 288dpi Samsung Galaxy Tab S touchscreen with built-in vibratory capabilities for testing. All tablets utilized Immersion's UHL Haptic effects library to generate vibration patterns [18]. The vibration effects used in the first study were SHORT_BUZZ (a constant, quick buzz) and TRANSITION_BUMP (a constant, quick and sharp pulse) at 100% intensity. For the second study only TRANSITION_BUMP at 100% intensity was used. Auditory tones were chosen from Android's native tone library. The

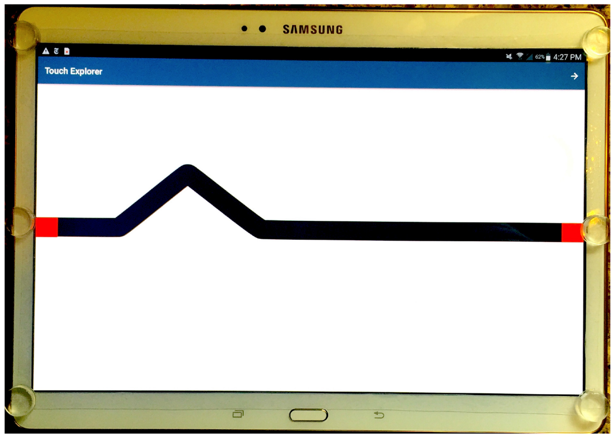

Fig. 1. A 10.5in. Samsung Galaxy Tab S with clear plastic around the boundaries of the active area of the screen and raised, plastic indicators used by the participant to quickly navigate into the top, middle, and bottom of the screen. A sample line profile from Study 1 is displayed on the screen with endpoints in red.

tones used in both studies were dual-tone multi-frequency (DTMF) tones TONE_DTMF_A (1,633Hz, 697Hz, continuous), TONE_DTMF_B (1,633Hz, 770Hz, continuous), TONE_DTMF_C (1,633Hz, 852Hz, continuous), and TONE_DTMF_D (1,633Hz, 941Hz, continuous), which correspond to the A, B, C, and D keys on the dial pad. TONE_CDMA_ALERT_CALL_GUARD was used exclusively for end points in Study 2 and is a notification sound for Android. Vibration signals and auditory tones were chosen for their highly distinguishable patterns and moderate frequencies. Additionally, each tablet was outfitted with boundaries around the active area of the screen and small plastic bubbles along the edges of the screen to aid individuals in navigating and staying within the active screen area (see Figure 1). From our previous work, we have found that these easy touchscreen adaptations greatly assist users in navigating and orienting themselves on the touchscreen.

All lines were displayed at approximately 8.9mm thick (a width previously shown by Giudice and colleagues to be a desirable line width on touchscreens [13]). All lines vibrated or played a continuous beep as the individual moved across the line. The bordered line width was 8.9mm (as all other lines in the study) and consisted of three line segments (top border, mid-line, and bottom border) each of equal thickness. The mid-line triggered feedback of the opposite type as its border. For example, a line with a vibration border always contained an audio midline. Border effects were triggered when the participant finger's centroid pixel (as explained in Section 1.1.1) contacted the border space. The location on the finger pad of this pixel remains constant until the participant removes the finger from the screen. Because the tablet chooses only one pixel of the entire finger pad in which to evaluate feedback, only 1 feedback type will be triggered. Should the participant's centroid pixel veer into border space, the border effect would be triggered.

Line profiles covered the entirety of the screen as shown in Figure 1. The lines in study 1 were approximately the same length, as they spanned the length of the screen with the exception of vertical lines. Due to the landscape orientation of the screen, vertical lines were shorter. In study 2, line lengths varied according to the number of inflection points. Each line had end points that were represented with a different feedback pattern of the same modality as the line itself to distinguish where the line starts and ends. This was determined to be beneficial to understanding the task based on findings from three pilot studies discussed in Study 1 in Section 3. Additionally, participants used only 1 finger to complete the tasks. This single point of contact is a hardware limitation as commercially available touchscreens used actuators, which vibrate the entirety of the screen and make localized feedback unattainable using multiple fingers.

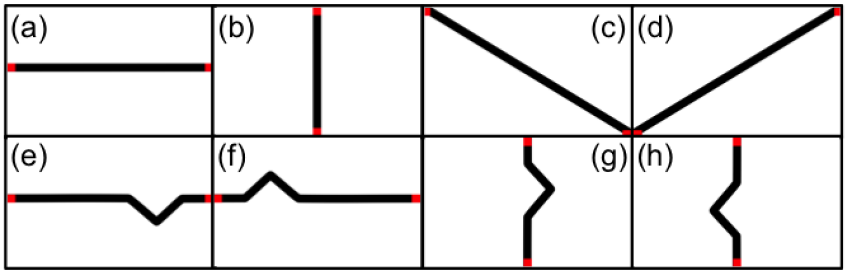

Fig. 2. Line orientations presented to each participant: (a) horizontal; (b) vertical; (c, d) diagonals; (e, f) horizontal obstacles; (g, h) vertical obstacles. Participants received a random version of (c) or (d), (e) or (f), and (g) or (h).

Both studies collected finger tracking data from the tablet, whether the participant was on or off the line, and a time stamp for each point taken at regular intervals. This data was used for analysis offline of deviation and time metrics for determining the efficiency and effectiveness of the line following methods. Both studies were approved by the university's Institutional Review Board and participants were provided informed consent.

3 LINEAR LINE PERCEPTION

3.1 Demographics

Seventeen individuals with BVI were recruited from Midwestern middle schools and summer programs for young individuals. Participants were 12 to 20 years old. Individuals received no incentive to participate and could leave at any time. Three of the 17 participants were pilot participants (as described in Section 3.3) and provided feedback on the initial study methods. These three participants were not included in data analysis. Of the 14 remaining participants, 2 were removed from analysis due to: (1) choosing not to participate in the experiment and (2) missing greater than 50% of their data due to auditory discomfort. The remaining participants are as follows: 8 male, 4 female; mode = 15 years.

Participants were given a short demographics survey to complete. We asked them to report on the severity of their visual impairment and when they were diagnosed. Of the participants that responded ($N = 9$), 5 reported having a significant impairment (no detail, only light) or worse. Six reported being impaired since birth, 1 reported being diagnosed in the last 1–5 years, and 2 reported greater than 10 years ago. We also collected data of their self-reported touchscreen usage measured in hours per day. Many participants found it difficult to quantify the number of hours spent on a touchscreen and responded "all day" to which the researcher and the participant reached an agreement quantified in hours. In general, participants reported using their touchscreen between 30min to 10h daily (mode = 8h).

3.2 Measures and Materials

In study 1, individuals were given six trials corresponding to six different line conditions (conditions: vibrating solid, vibrating dashed, vibrating midline with an auditory border, auditory solid, auditory dashed, and auditory midline line with a vibrating border). For vibrating lines, the vibration pattern used for the overall line profile was SHORT_BUZZ (a buzzing vibration), with end points in TRANSITION_BUMP (a pulsing vibration). The pattern used for the borders of the vibratory border line was similarly SHORT_BUZZ. For auditory lines, TONE_DTMF_A was used for the overall line profile and TONE_DTMF_B for the end points. The audio profile used for the borders of the auditory border was TONE_DTMF_A.

In each of the six trials, participants received five line orientations (horizontal, vertical, diagonal, horizontal obstacle, and vertical obstacle; see Figure 2). Two of these orientations were "obstacle" orientations defined as unexpected, sharp direction changes within an otherwise straight line. Orientations were presented in a random

Table 1. Participant Summary

#	Age	Gender	Impairment*	Touchscreen Aid	Handedness
1	15	F	3	None**	Left
2	12	M	4	VoiceOver	Right
3	15	F	3	VoiceOver	Left
4	14	M	N/A	None	Right
5	16	M	2	TalkBack	Right
6	15	M	3	VoiceOver	Both
7	15	M	N/A	Other**	Right
8	16	F	N/A	VoiceOver	Right
9	15	M	2	Other	Right
10	20	F	1	None	Left
11	19	M	3	VoiceOver	Both
12	19	M	1	Other	Right

*Level of impairment was selected from one of the four categories. 1 = Some Impairment (glasses), 2 = Moderate Impairment (strong prescription), 3 = Significant Impairment (only light), 4 = Complete Impairment (no light).
**Not all participants used a touchscreen accessibility aid. Those in the "None" category had a condition that did not prevent them from using a touchscreen or were able to use strong prescription glasses to use their touchscreen. Those in the "Other" category preferred to use other methods such as screen magnifiers, inverted colors, and large text.

order per line condition. For line orientations that had alternative representations (left or right diagonal, for instance), the participant was randomly given only one version to trace. Each individual explored 30 lines total.

Half of the participants received the vibration-based line conditions first (solid, dashed, vibrating line with auditory border) and the other half received the auditory-based line conditions first (solid, dashed, auditory line with vibratory border). To understand whether the participant understood the line correctly and was able to create a correct mental representation of the line, be it in a more "visual" or a spatial sense, participants were asked to redraw the line on a piece of paper after each line trial. The participant used their preferred writing tool and a piece of paper roughly the size of the tablet screen.

At the end of each session, a questionnaire assessing the individual's preferences was administered. This questionnaire included questions on the individual's preferred line conditions, usability of the application, and perceived difficulty level of each line condition.

3.3 Procedure

Individual sessions took approximately 2h to complete. Each session included the demographics survey, a training period, the line following tasks, and the post-questionnaire. After completing the demographics form, individuals were introduced to the hardware and the minor modifications made to assist them in navigating on the screen. The screen was darkened and no visual information was present on the screen for the duration of the study. Participants who wore glasses or other aids were asked to remove them. Furthermore, participants who rated their visual impairment as 1 (some impairment requiring glasses) or 2 (moderate impairment requiring strong prescription glasses) in Table 1 were blindfolded for the task. This was done to ensure a consistent testing environment among participants who may have varying degrees of visual impairments, though we note that the visual display of the graphics is an advantage of the touchscreen platform itself and would be beneficial for individuals who have some level of functional vision.

A pilot of the procedure was completed with three participants. After receiving feedback from this pilot study, we introduced end points to the lines and affixed boundaries to the screen to help participants better complete

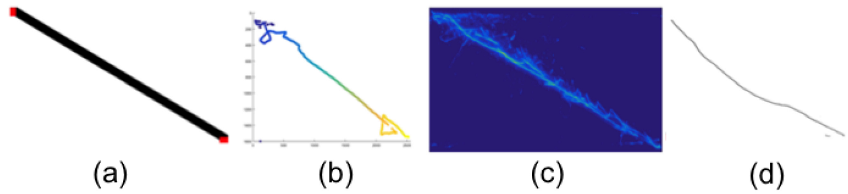

Fig. 3. An example of the data collected for all participants. (a) The line as represented on the tablet with end points denoted in red; (b) individual finger position data collected during exploration (blue refers to where the participant began tracing and yellow where they ended); (c) a composite density map of every participant's finger position for the given line (dark colors indicate low density and light colors indicate high density); and (d) the individual participant's interpretation of the line via drawing.

the task. Start and end points provided the participants with defined start and end goals. The boundaries assisted users in remaining in the active area of the touchscreen. This allowed them to physically align themselves with the horizontal and vertical edges of the screen and provided a reference for how they were constrained in the digital space.

Participants were provided a short training period for each line condition (one horizontal, one vertical) at the start of each of the six conditions. The training period had no fixed time for completion. During training, individuals were told that all lines would start and end at the boundaries of the screen, and they were instructed to begin their explorations in the top left corner of the screen, as from our pilot studies, we learned that this is representative of how individuals with BVI are most often taught to explore tactile images. After the individual completed the training period, data collection commenced. Individuals were allowed to work at their own pace to explore each line segment and were allowed breaks when needed.

When the participant believed they had sufficiently explored the line and could re-create the line on paper, they alerted the experimenter who provided the paper and preferred writing tool. This process was repeated for all line representations. At the end of the study, individuals completed a post-questionnaire.

3.4 Results

Data collected during the study included: participant position data, individual drawings, a demographic questionnaire, and the post-questionnaire responses. For each participant, we compared the original line representation displayed on screen (Figure 3(a)), with individual finger position data (Figure 3(b)), aggregated finger position data of all participants for that particular line on a density map (Figure 3(c)), and the individual's drawing of the line (Figure 3(d)). The individual finger position coordinates were used to determine the average deviation distance from each line by each participant. Average deviations were computed and plotted using MATLAB 2015a and analyzed using IBM SPSS Statistics 2015. Density maps were also created in MATLAB, which provide a visual representation of compiled finger position data for all participants for each line representation and condition. The dark blue color represents low density of finger positions, and the bright blue to green represent high density.

The drawings re-created on paper by each individual for each line were used to evaluate the reproduction accuracy of the displayed lines. The criteria for an accurately reproduced line involved a clear understanding of the three parts of the traced line segment: (1) start point, (2) end point, and (3) general line profile. Accuracy was evaluated dichotomously. Participant interpretations were determined to be either correct or incorrect in accordance with the aforementioned criteria. In evaluating the general line profile, the following components were considered: direction (or angle), straightness of the line, and unexpected deviations or breaks in the line. For ambiguous interpretations, participants were asked to clarify verbally or with gestures. The experimenter used all of the above parameters to determine if the general sense of the line profile had been acquired or if important

Table 2. Line Condition Summary (All Lines)

	VS	VD	AS	AD	AB	VB
Mean Deviation from Line (mm)	14.23	16.43	15.38	16.51	13.64	13.11
Rankings by Deviation	2	5	4	6	2	1
Mean Reproduction Accuracy	67%	71%	62%	72%	67%	73%
Rankings by Accuracy	5	3	6	2	4	1
Preference*	92%	90%	42%	70%	56%	90%

Note: *Individuals who rated the line condition as Very Easy, Easy, or Feasible to follow.

Table 3. Line Condition Summary (Obstacle Lines Removed)

	VS	VD	AS	AD	AB	VB
Mean Deviation from Line (mm)	14.47	15.98	13.46	16.67	12.56	11.47
Rankings by Deviation	4	5	3	6	2	1
Mean Reproduction Accuracy	81%	87%	81%	93%	90%	90%
Rankings by Accuracy	6	4	5	1	2	3

features were missing. Questionnaire responses were collected for qualitative feedback on user preferences, likability, and usability.

Results are presented below for two scenarios: (1) all line orientations (Table 2) and (2) lines without obstacles (Table 3). One of the biggest qualitative take-aways from this first line following study was the need for additional forms of feedback when obstacles are present in the line. We addressed non-linear lines in Study 2 presented in Section 4. For Study 1, we looked at the results under these two conditions to explore line following abilities with and without obstacles, with the understanding that the obstacle conditions were quite difficult for users to follow without any additional identifiers or cues.

Results pertaining to line deviation and reproduction accuracy are displayed in Tables 2 and 3. In these tables, VS refers to Vibrating Solid lines; VD, Vibrating Dashed; AS, Auditory Solid; AD, Auditory Dashed; AB, Auditory Border; and VB, Vibrating Border.

The experimenter alternated which feedback to give first (auditory lines or vibratory lines), and thus, to determine the existence of any statistically significant order effects, two Repeated Measure ANOVAs (2×6; order of presented lines, line condition) were run for both correctness of drawn line and deviation from line. No order effects were found for either correctness (Line Condition: $F(5,7) = 0.90$, $p = 0.58$, $\eta^2 = 0.60$; Line Condition $\times$ Order: $F(5,7) = 0.84$, $p = 0.60$, $\eta^2 = 0.58$) or deviation (Line Condition: $F(5,7) = 0.74$, $p = 0.64$, $\eta^2 = 0.55$; Line Condition $\times$ Order: $F(5,7) = 4.02$, $p = 0.14$, $\eta^2 = 0.87$).

Repeated Measures ANOVAs were performed to investigate the average deviation scores, as well as the average correctness of drawn lines, for the six line conditions. Assuming sphericity (Correctness: $\chi^2(14) = 21.17$, $p = 0.12$; Deviation: $\chi^2(14) = 15.68$, $p = 0.37$), no statistically significant differences were found between the means of the deviation scores nor the correctness scores (Correctness: $F(5,40) = 1.27$, $p = 0.30$, $\eta^2 = 0.14$; Deviation: $F(5,40) = 1.39$, $p = 0.25$, $\eta^2 = 0.15$). While there was not a significant difference between the conditions, there are notable findings and observations that have practical implementations, which are discussed below.

For all lines, including those with obstacles, the line conditions that promoted the most precise following (e.g., least amount of deviation from the line) were the two border conditions (vibratory line with auditory border and auditory line with vibratory border), as shown in Table 2. The average deviations of the vibratory and auditory border conditions were 13.11 and 13.64mm, respectively. Given that the average width of the index finger pad is approximately 16–20mm [4], these results are quite promising.

Density maps of participant tracing profiles with the border conditions validated the fine tracking with which users were able to trace the lines in these cases, showing high densities on or very near to the line displayed.

We also note that the vibrating solid condition was a close third, with an average deviation of 14.23mm. While borders may enable users to more finely trace lines, this finding indicates that it may not be necessary to represent all lines with borders within a graphic to still obtain good tracking performance. This is particularly relevant if resolution is an issue, which will be the case on smaller screen sizes.

When looking at the drawn line recreation for all lines, average accuracy was between 62–73%, with the best conditions being the vibrating border and auditory dashed conditions. We note that all of the representations were quite close in comparison. When the obstacle lines were excluded, accuracy greatly improves to 81%–93%, with the best conditions again being auditory dashed, vibrating border, and auditory border. Average deviation distances also improved when lines with obstacles were removed, with the border conditions promoting the most precise following of the line once again. Results of performance for lines without obstacles are displayed in Table 3. A similar trend was observed the six line conditions in average deviation compared with the all lines case.

One-way ANOVAs were also run to compare line orientations (horizontal, vertical, and diagonal) across the different feedback groups (e.g., vibrating solid, auditory solid) for both line deviation and correctness of line interpretation.

A statistically significant difference in means was found for line deviation, but Levene's test showed that the variances for line deviations across the feedback groups were not equal, $F(2{,}178) = 109.99$, $p < 0.001$. A Welch F-test was run to compensate for the violation and the difference between the line deviation means in each feedback group was still significant, $F(2{,}178) = 41.47$, $p < 0.001$, partial $\eta^2 = 0.32$.

A Tukey post hoc test revealed statistically significant differences for vertical orientations compared to horizontal and diagonal orientations. Vertical lines had significantly larger deviations than either horizontal or diagonal lines. This is surprising, given that vertical lines as presented in this study were shorter due to the orientation of the screen. This may be attributed to being less familiar with movement downwards as braille readers read and are more familiar with horizontal movement. This difference is notable, as it would suggest that practitioners consider screen orientation and using landscape profiles when displaying graphics on the screen.

3.5 Discussion

Overall, the findings of the current study were very promising, suggesting that users can follow lines with or without obstacles with deviations as small as 13.11mm, smaller than the width of an average adult finger pad. Additionally, users could re-create what they felt or heard on screen with accuracies up to 73% (all line orientations) and 90+% (without obstacles). Given that it is challenging for individuals with BVI to create spatial mental representations and then to have the fine motor skills needed to redraw them on paper, these accuracies were very encouraging. We acknowledged a limitation to having BVI individuals re-create the line without tactile assistance. Being that many of our participants were young and had yet to encounter a tactile assistive drawing device, we opted for the simple approach of marker (or pen) on paper. The paper itself was roughly the same size as the screen so participants could draw with the boundaries as reference. In addition to drawing, participants were asked to clarify uncertain or illegible recreations using a combination of verbal descriptions and using their fingers or arms. It is important to note that we were not evaluating the precision of the drawing, only if the general interpretation was correct.

Results suggested that the border conditions were the optimal representation for fine tracing. They had the smallest average deviation distance from the line and relatively high accuracies of recreating the line drawing. This is consistent with our hypothesis that border conditions may be adventageous when users begin to stray from the line profile, mitigating the zigzag motion that often occurs in line following on flat surfaces. Although the auditory border condition was not highly preferred by participants, the vibratory border condition was, and the two border conditions had a high, significant correlation with one another in terms of perceived difficulty ($r(9) = 0.90$, $p < 0.01$). This highlights the importance of feedback customization according to personal preference, something that can be provided via the touchscreen platform.

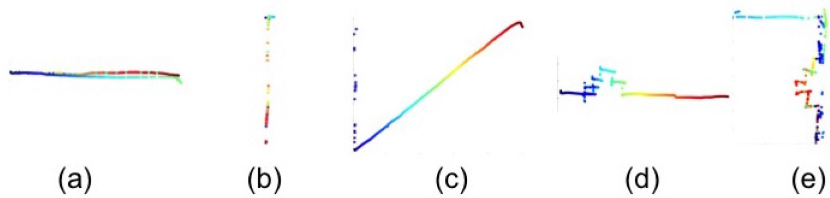

Fig. 4. Finger position data for the participant using the thumb-anchor procedure to trace lines.

Bordered lines may be useful to highlight the importance of a particular line, such as a trendline or a bar on a graph, or for cases of complex, feedback-rich graphics where a particular path is notable, such as roads on maps. Given that complex graphics may be composed of multiple lines, it may not always be desirable to represent every line with borders, and fine tracing of every line may not be necessary. In this case, the solid line representation case would be a sufficient alternative, and would reduce complexity and enhance resolution of the multimodal image. The vibrating and auditory solid line conditions performed quite well in terms of accuracy, individual preference, and deviation from the line during tracing.

Our results suggest that vibrating lines tend to be preferred over auditory lines, have shorter average deviation distances than auditory lines, and tend to be re-created more accurately in all cases. This finding supports the need for feedback beyond auditory feedback, which is currently the state of the art in many assistive technology devices. These findings also highlight the viability of vibrations. We suspect that vibrations were preferred over auditory sounds, because vibrations provide a direct, touch-based form of feedback. This may be more natural for longer and continuous explorations such as the line following task in this work. Users also suggested that vibrations offered more privacy and could be unobtrusive to others around them and so deemed this as advantageous over auditory cues that would require headphones. Vibrations are embedded in many existing commercially available technologies, but are currently underutilized, commonly being used only for tertiary cuing. Findings such as this should encourage designers of information access technologies to use all modalities available for conveying information and to consider raising the touch modality as a primary interaction style.

Dashed lines were incorporated into the study due to their similarity to raised, embossed graphics. It was observed throughout the study, however, that dashed lines appeared to be the most frustrating lines for participants to follow due to the tendency to "lose the line" between dashes. From these results and because of the compelling evidence of the solid and border line conditions, the outcomes do not seem to support the use of dashed line representations. At minimum, more research needs to be done to determine the optimal spacing between dashes necessary to alleviate user frustration. Effectiveness of perceiving dashes as continuous lines was limited by the resolution of the finger pad itself.

Many participants had suggestions on how to improve tracing of lines and graphics on a touchscreen using vibratory and auditory feedback. These suggestions include the above participant's (Figure 4) anchoring strategy (keeping the thumb at the bottom of the screen while the pointer finger explores the line), creating a custom stylus to attach to the finger pad to allow for finer tracing, and implementing more feedback cues to indicate the direction of curves. Feedback gradients (e.g., sound growing louder or vibrations becoming stronger when following a line from one end point to the next) were the most common suggestions to improve line tracing on the touchscreen.

4 NON-LINEAR LINE PERCEPTION

4.1 Research Questions

Given that the major challenge in Study 1 was following non-linear paths, the goal of this second study was to promote effective tracing of non-linear paths on touchscreens using additional feedback strategies. From user input received in the first study, indicators at key points in the non-linear profile are hypothesized to help mitigate the difficulties currently experienced.

We proposed 2 possible solutions: (1) Indicate the minimum and maximum inflection points of all curves in the lines with a single sound cue (herein referred to as 1-point lines; first row of Figure 5) and (2) indicate the current user's position on the line as they near the minimum and maximum inflection points of the curves with additional sound cues, varying in pitch (herein referred to as 3-point lines; second row of Figure 5). The goal of this study was to determine how much information (in the form of inflection points) is necessary to promote precise line following and quick perception of a curving line that extends across the width of the screen.

We hypothesized single cues at the inflection and deflection points were sufficient for successful line perception as evaluated by time and finger deviation from the line during tracing. Single points offer simplicity in terms of design and user following. The second condition of multiple points served to investigate the component of preference and to see if there exists any potential advantages of including more information about the curve. The findings from this study will help formulate guidelines on how to represent non-linear profiles to promote efficient line following when reading graphics on touchscreen, which we discuss in Section 5.

4.2 Methods

For this study, we employed the same methods used in the first line following study presented in Section 3. The one addition is that Study 2 includes audio cues at the minimum and maximum inflection points of each curve in the line (see Figure 5), as described above.

Demographics. Eleven individuals were recruited from an assistive technology conference (5 male, 1 female; mode = 42 years) and a midwestern summer program for young individuals with BVI between 12 and 20 years old (5 female; mode = 16 years) All participants had some form of blindness or visual impairment. The conference participants received a gift card to encourage participation at the conference whereas the summer program participants volunteered to participate and received no incentive per the program director's request. All participants could leave at any time without repercussions. Of the 11 participants, 2 from the summer program were not included in analysis due to choosing not to participate in the experiment at the time of their session.

As the summer camp participants were younger than the conference participants, data from the two groups were not be compared to one another, but instead were pooled and analyzed together as deemed appropriate from preliminary analysis between the two groups. For analyses combining the two groups, the data was checked for outliers in preliminary analysis. Any outliers relevant to a specific statistical test were first removed from the analysis pool and are addressed in the sections below.

Participants were given a short demographics survey to complete. From this survey, we determined the most common diagnosis of visual impairment was Retinopathy of Prematurity ($N = 4$). In addition to asking participants of their impairment, we asked them to consider when they were diagnosed. Of the participants that responded ($N = 7$), 5 reported having been diagnosed at birth. We also collected data of their self-reported touchscreen usage measured in hours per day. The most common reply was "all day" (66.7%), to which the researcher and the participant reached an agreement quantified in hours. See Table 4 for complete demographic information.

4.3 Measures and Materials

The sessions consisted of two trial conditions: (1) lines with only the inflection and deflection points marked with a single auditory cue (1-point lines); and (2) lines with additional points near the inflection and deflection points, which varied in pitch and depended on participant location (3-point lines; see Figure 5).

The vibration pattern used for the overall line profile was TRANSITION_BUMP (a pulsing vibration), with end points in TONE_CDMA_ALERT_CALL_GUARD (a notification sound). The tones for the points on the line consisted of three pitches—low, medium, and high, relating to the participant's position on the line. Lower pitches

Table 4. Participant Summary

#	Age	Gender	Impairment*	Onset	Handedness
1	59	M	ROP	Birth	Left
2	36	M	ROP	17	Left
3	42	M	LCA	Birth	Right
4	42	M	IIH	37	Right
5	62	F	Unknown	Unknown	Both
6	27	M	ROP	3	Right
7	16	F	ROP	Birth	Left
8	19	F	TP	Birth	Left
9	16	F	LCA	Birth	Left

*ROP = Retinopathy of Prematurity; LCA = Lebers Congenital Amerosis; IIH = Idiopathic Intracranial Hypertension.

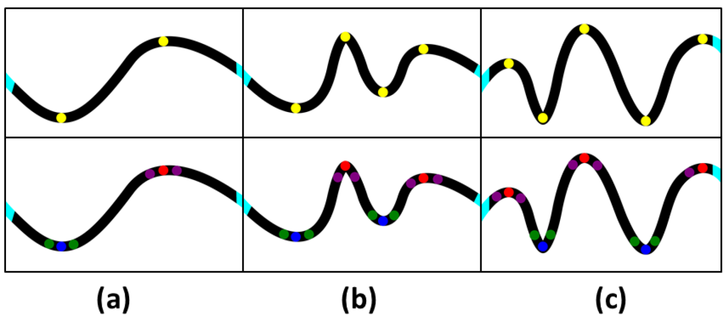

Fig. 5. An example of a line in each of the 3 difficulty levels among 1-point (top row) and 3-point (bottom row) lines. (a) Easy Difficulty; (b) Medium Difficulty; (c) Hard Difficulty. End points of the line are in blue. Auditory inflection and deflection points are marked along the line.

corresponded to lower positions on the curve. For the 1-point lines, the audio cue was TONE_DTMF_D. For the 3-point lines, the audio cues were A–D with tone A being the lowest pitch and D being the highest.

Auditory points were chosen over vibratory points to separate directional information from line information via modality to avoid sensory overload. Using cues from different modalities is thought to be the best way for quick differentiating of information and to enhance performance (e.g., References [19, 24]).

Participants were asked to completely trace a set of randomized lines consisting of both the 1- and 3-point line conditions. Individuals were given a set of lines to trace in each of the two trials. Eight lines per trial (16 total) were given to the conference adults whereas six lines per trial (12 total) were given to the participants of the summer camp due to time constraints. As there were only three participants in the summer camp category, we opted to include all lines from this data set in the pooled analysis. In the group that received 6 trials, every participant received at least one from each difficulty category for both the 1- and 3-point conditions. The overall distribution among each category was comparable, though not equal. The medium difficulty category was slightly higher than the easy and hard categories in the 1-point condition and the hard category was slightly higher than the easy and medium categories in the 3-point condition.

Participants were provided a short training period that consisted of a line having only 1 deflection point. Half of the participants received the 1-point condition first and the other half received the 3-point relative pitch condition first. Lines were presented in a random order per trial and varied in difficulty. Line difficulty was determined by the number of deflections in the line. The easiest condition included only 1 deflection; the medium difficulty, 2 deflections; and the hardest, 3 deflections (see Figure 5).

Table 5. Average Data from Line Conditions by Difficulty

Difficulty	Deviation (mm)	Time (s)
1-Point		
Easy	7.56	65.55
Moderate	8.35	92.90
Difficult	7.79	102.65
3-Point		
Easy	7.42	63.26
Moderate	8.27	83.89
Difficult	8.90	111.20

4.4 Procedure

Individual sessions took approximately 1h to complete. Similar to Study 1, each session included the demographics survey, a training period, the line following tasks, and the post-questionnaire. After completing the demographics form, individuals were introduced to the hardware and modifications made to assist them in navigating on the screen (see Figure 1). The screen was dimmed for the duration of the study to not display any of the lines visually on screen to the participants. Participants who may have benefited from residual vision were blindfolded for the task.

Training was done at the start of both conditions. During training, individuals were told that all lines would start and end at the left and right boundaries of the screen. They were instructed to begin their explorations in the top left corner of the screen. After the individual completed the training period, data collection commenced. Individuals were allowed to work at their own pace and use their own strategies to explore each line segment completely but were given no more than 3min. This time limit was imposed to keep the participant focused on the task and to avoid spending an unreasonable amount of time exploring any one line. At the end of the study, individuals completed a post-questionnaire regarding the lines and their difficulties.

4.5 Results

Data collected in this study included finger position data on the tablet, time data, a demographic questionnaire, and the post-questionnaire responses. For a more detailed description of how the above were analyzed, please see Section 3.4.

Table 5 details the average time data and distance participants deviated from the line during tracing according to condition and line difficulty. From the calculated deviations, the data revealed participants in both the 1- and 3-point relative pitch conditions performed nearly equally in terms of average line deviation. The overall average deviation distance was 7.96 and 8.33mm, respectively. A similar trend was observed when sorting the data by level of difficulty, as in Figure 7.

One-Way ANOVAs were performed to investigate average deviation by both group and difficulty for both 1- and 3-point lines overall. While no significant difference was found for average deviation and difficulty, a statistically significant difference in the means was found for time and difficulty ($F(2,15) = 12.27$, $p = 0.001$). Tukey's HSD revealed that lines in the difficult ($p < 0.001$) and moderate ($p = 0.46$) categories tended to take longer to trace than easy lines. This result, while unsurprising, demonstrates increasing difficulty of the lines in each category, and confirms that the number of deflections was representative of increased difficulty.

Separating the 1- and 3-point groups, one-way ANOVAs were performed and a statistically significant difference between the 3 difficulty groups among the 1- and 3-point condition lines was found ($F(2,6) = 5.21$, $p = 0.05$; $F(2,6) = 5.23$, $p = 0.04$). Tukey's HSD revealed a statistically significant difference in average time between the easy and difficult line conditions for both 1- and 3-point lines ($p = 0.04$; $p = 0.04$). Participants tended to spend significantly more time exploring the difficult lines than the easy lines, but not necessarily moderate lines in either condition.

While no statistically significant difference was found for either the 1- or 3-point lines for finger deviation and difficulty, the deviations were small overall. The average deviations were approximately half a finger pad's width. Given the resolution of detecting vibrations with one's finger pad in combination with the line vibration, the 1- and 3-point feedback conditions helped to facilitate accurate line following.

Time data was also taken to assess if either condition affected the participant's time spent on the task. Using IBM SPSS 2015, an independent samples t-test was performed to compare completion time between the 1- and 3-point relative pitch conditions ($t(16) = 0.51$, $p = 0.959$). On average, participants did not spend more time exploring the 1-point lines ($M = 85.83$s; $SD = 20.91$) than the 3-point relative pitch lines ($M = 85.24$s; $SD = 26.60$).

At the end of the study, participants were asked to rate the difficulty of each trial condition on a 5-point Likert scale (Very Difficult, Difficult, Feasible, Easy, Very Easy). When asked to rate the difficulty of the 1-point line condition, 77.8% ($N = 9$) responded that the lines were feasible or better to follow with a majority of the participants remarking that the lines were Feasible or Easy. When asked to rate the difficulty of the 3-point relative pitch line condition, only 55.6% rated the lines above feasible. However, 44.4% of participants preferred the relative pitch condition whereas only 22.2% preferred the single point line condition. These results are illustrated in Figure 8.

We also asked participants about their preference as to what would assist them the most when following a non-linear line on a touchscreen. They were given the option of selecting the 1-point condition, 3-point relative pitch condition, or something else. If participants thought of another solution, then they had the opportunity to discuss it with the experimenter and their preference was marked as "other," which is further discussed in Section 4.6. Neither time data nor deviation data show a statistically significant difference between the 1- and 3-point groups, so participant preference for the amount of additional feedback may play a bigger role than the two feedback groups themselves.

4.6 Discussion

The data demonstrated very small differences in average deviation from the traced line and average time spent tracing the line between both the 1- and 3-point relative pitch conditions (see Figure 5). On average, participants deviated about half a fingerpad's width away from the line with additional help from the key points. Participants were also able to completely trace the lines from start to end in an acceptable amount of time, around 1–3min, depending on difficulty.

Only a small average deviation (7.96 and 8.33mm) from the line profile was observed across both the 1- and 3-point conditions. This reflected the participant's ability to follow the vibrating curve with auditory assistance with only minor deviations. In Figure 7, the trend implies that as difficulty increased, so did average deviation from the line. While this figure seems to imply a large disparity between the 1- and 3-point lines in the Difficult category, the 1mm difference shown between the two groups was not found to be significant.

As the average line deviations per 1- and 3-point condition were similar, it appeared that preference (more information vs. less information) may be the most important factor in determining how best to represent a non-linear line to BVI users in the digital space. In the post-study questionnaire and discussion, 45% preferred to have more information about a line and preferred the 3-point condition. This was especially true when participants were presented with a hypothetical scenario that involved tracing a more complex graphic, despite the perceived increase in difficulty of tracing 3-point lines.

Most participants followed the line precisely and methodically, but two of the nine participants employed other strategies to help them follow the line to the end. These participants preferred to zigzag or explore line edges with circular movements rather than follow the lines pragmatically. This was most notably conveyed in

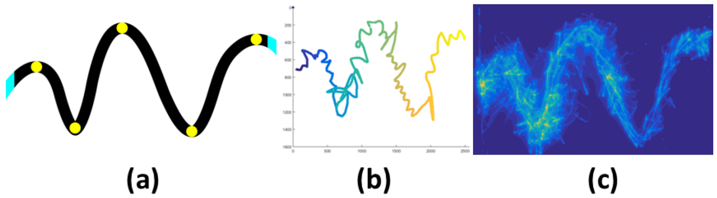

Fig. 6. A composite image of a participant's finger position (blue refers to where the participant began tracing and yellow where they ended) (b) as compared to the original 1-point line (a) and a density map of all participant finger positions for that particular line (c). Dark colors indicate low density and light colors indicate high density.

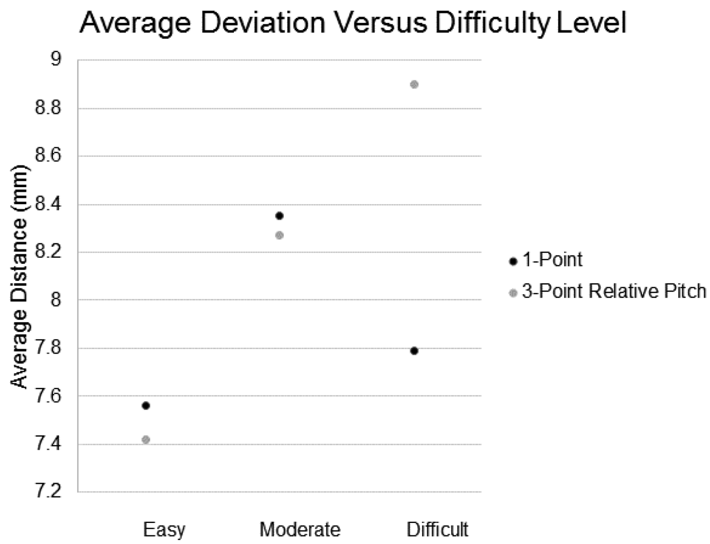

Fig. 7. A comparison of average line deviation distance and line difficulty among the 1- and 3-point relative pitch lines.

the scatter plot of Figure 6. Both participants remarked that these strategies only made the line easier and quicker to follow, but not easier to perceive. Of the two participants who chose to employ such strategies, one participant stood out on both average time to complete the line and average deviation away from the line. The participant's average time (49.44s) and average deviation (6.70mm) were lower than the average (85.24s; 8.04mm).

Many participants felt that the 3-point relative pitch lines were more difficult than their 1-point counterparts. Even so, participants preferred these lines as they preferred more information to less information when following curved lines. Some participants also had more suggestions as to what would help them better follow a curved line on a touchscreen. Those suggestions included the option of placing more relative-pitch auditory points along the line, adding more points spaced along the line, and adding a gradient-based, continuous sound all along the line. Multitouch support was also often suggested, but as current commercial touchscreens do not have such a feature, we are investigating ways that may mimic the benefits of multitouch. These include implementing multiple pointers at the program or app level to correspond to multiple finger touches and designating one pointer as the "active" or movable pointer for tracing on the touchscreen.

5 GUIDELINES FOR DESIGNING GRAPHICS FOR NON-VISUAL USE

The data and user feedback garnered from both studies serve a greater purpose than to demonstrate the feasibility of tracing and understanding line profiles on touchscreens. To inform designers and practitioners on some of

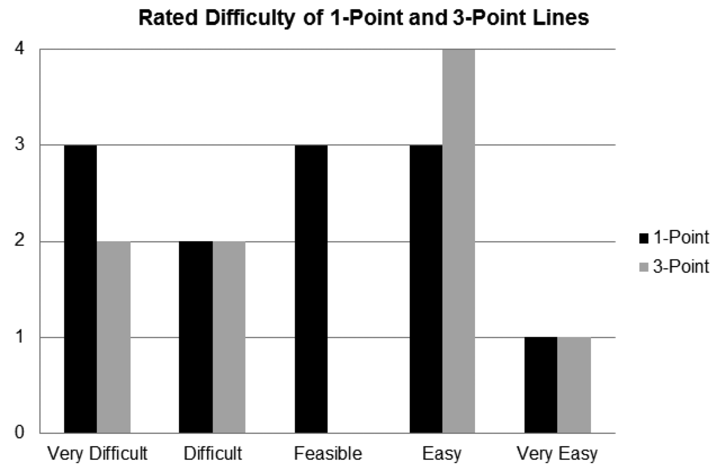

Fig. 8. Participants' ratings of difficulty of the 1- and 3-point lines.

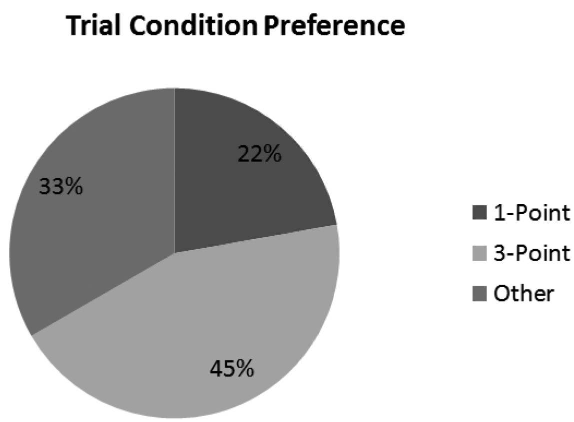

Fig. 9. Participant preference for the method of facilitating curved line following on a touchscreen.

the best practices that we have observed, we share some of the primary preferences that have emerged toward establishing guidelines for how to create multimodal graphical components on touchscreens. Although many of these guidelines echo suggestions from previous research using multimodal feedback effectively to convey non-visual graphics (e.g., References [1, 13, 17]), these are specific to vibratory touchscreen use and the tracing of lines using one finger.

(1) Use start and end points on lines that provide a different feedback signal either of the same or different modality.
(2) Vibration-only and audio-only lines are sufficient for line tracing and understanding.
(3) Bordered lines encourage finer, more precise tracing.
(4) For non-linear lines, an alternative feedback signal is necessary for unexpected complexities in the line profile such as abrupt deviations, inflections, and deflections.
(5) Common tracing strategies (e.g., zigzagging on a line or circling to find the continuation of the path) should be taken advantage of in both designing lines for non-visual use as well as when teaching users how to trace lines on a touchscreen.

(6) Encourage users to take advantage of "multitouch" and anchoring techniques by teaching them how to use other fingers as points of reference during exploration.
(7) Consider horizontal orientations for displaying graphical entities as opposed to vertical to provide a more natural experience when scanning and tracing.

6 CONCLUSION

In this work, we have demonstrated the promise of non-visual line following on flat surfaces like commercial touchscreens. The results of these studies inform future implementation of tactile information on such readily available devices, which is of direct benefit to not only BVI individuals, but individuals who may not be able to visually focus on the screen to view simple graphics and interface components.

The guidelines presented here form a foundation for how to represent fundamental graphical components using multisensory feedback on touchscreen platforms. This work provides a springboard for the exploration of more complex graphics and foreshadows a promising future where touchscreens may become even more accessible for displaying highly visual content. Solid vibratory and auditory lines may serve as a means to investigate a graphic, such as a bar chart or diagram of the parts of a flower, wherein the lines serve as a means to garner information. Bordered lines may be used when the line itself is notable, such as trend lines on a graph, or in feedback-rich spaces to keep individuals within the boundaries of the path, such as on a road on a map. When lines curve or turn, additional feedback at the inflection point will help users stay on track. Future work will build upon this fundamental study to explore more complex graphics and spatial organizers to further probe the affordances and limitations of multimodal feedback on touchscreens in the context of visual imagery.

ACKNOWLEDGMENTS

The authors thank all of the participants in the user studies conducted in this work.

REFERENCES

[1] L. M. Brown, S. A. Brewster, S. A. Ramloll, R. Burton, and B. Riedel. 2003. Design guidelines for audio presentation of graphs and tables. In *Proceedings of the International Conference on Auditory Display*.

[2] B. Chua and P. Mitchell. 2004. Consequences of amblyopia on education, occupation, and long term vision loss. *Brit. J. Ophthalmol.* 88, 9 (2004), 1119–1121.

[3] J. C. Craig. 1993. Anomalous sensations following prolonged tactile stimulation. *Neuropsychology* 31, 3 (1993), 277–291.

[4] K. Dandekar, B. I. Raju, and Mandayam A. Srinivasan. 2003. 3D finite-element models of human and monkey fingertips to investigate the mechanics of tactile sense. *J. Biomech. Eng.* 125, 9 (2003), 682–691.

[5] P. W. Davidson. 1972. Haptic judgments of curvature by blind and sighted humans. *J. Exp. Psychol.* 93, 1 (1972), 43–55.

[6] DO-IT. 2012. World Wide Access: Accessible Web Design. Retrieved from http://www.washington.edu/doit/world-wide-access-accessible-web-design.

[7] J. P. Fritz, T. P. Way, and K. E. Barner. 1996. Haptic representation of scientific data for visually impaired or blind persons. In *Proceedings of the CSUN Conference on Technology and Disability*. Citeseer.

[8] E. Gentaz and Y. Hatwell. 2004. Geometrical haptic illusions: The role of exploration in the Maijller-Lyer, vertical–horizontal, and Delboeuf illusions. *Psychonom. Bull. Rev.* 11, 1 (2004), 31–40.

[9] N. A. Giudice. 2006. Wayfinding without vision: Learning real and virtual environments using dynamically updated verbal descriptions. In *Proceedings of the Conference on Assistive Technologies for Vision and Hearing Impairment (CVHI'06)*.

[10] N. A. Giudice, J. Z. Bakdash, and G. E. Legge. 2007. Wayfinding with words: Spatial learning and navigation using dynamically updated verbal descriptions. *Psychol. Res.* 71, 3 (2007), 347–358.

[11] N. A. Giudice, M. R. Betty, and J. M. Loomis. 2011. Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. *J. Exp. Psychol.: Learn., Mem., Cogn.* 37, 3 (2011), 621.

[12] N. A. Giudice, R. L. Klatzky, and J. M. Loomis. 2009. Evidence for amodal representations after bimodal learning: Integration of haptic-visual layouts into a common spatial image. *Spatial Cogn. Comput.* 9, 4 (2009), 287–304.

[13] N. A. Giudice, H. P. Palani, E. Brenner, and K. M. Kramer. 2012. Learning non-visual graphical information using a touch-based vibro-audio interface. In *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 103–110.

[14] N. A. Giudice and J. D. Tietz. 2008. *Spatial Cognition VI: Lecture Notes in Artificial Intelligence*. Vol. 5248, Chapter Learning with Virtual Verbal Displays: Effects of Interface Fidelity on Cognitive Map Development. Springer, Berlin, 121–137.

[15] C. Goncu and K. Marriott. 2011. GraVVITAS: Generic multi-touch presentation of accessible graphics. In *Proceedings of the Conference on Human-Computer Interaction*. Springer, 30–48.
[16] J. L. Gorlewicz, J. Burgner, T. J. Withrow, and R. J. Webster III. 2014. Initial experiences using vibratory touchscreens to display graphical math concepts to students with visual impairments. *J. Spec. Edu. Technol.* 29, 2 (2014), 17–25.
[17] W. Grussenmeyer and E. Folmer. 2017. Accessible touchscreen technology for people with visual impairments: A survey. *Trans. Access. Comput.* 9, 2 (2017), 6:1–6:31.
[18] Immersion. 2015. Immersion Developer Zone. Retrieved from http://www2.immersion.com/developers/.
[19] R. L. Klatzky, N. A. Giudice, C. R. Bennett, and J. M. Loomis. 2014. Touch-screen technology for the dynamic display of 2D spatial information without vision: Promise and progress. *Multisens. Res.* 27 (2014), 359–378.
[20] R. L. Klatzky, S. J. Lederman, and V. A. Metzger. 1985. Identifying objects by touch: An "expert system". *Percept. Psychophys.* 37, 4 (1985), 299–302.
[21] R. L. Klatzky, S. J. Lederman, and C. Reed. 1987. There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *J. Exp. Psychol.: Gen.* 116, 4 (1987), 356–369.
[22] S. J. Lederman and R. L. Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cogn. Psychol.* 19 (1987), 342–368.
[23] S. J. Lederman and R. L. Klatzky. 2009. Haptic perception: A tutorial. *Atten., Percept. Psychophys.* 71, 7 (2009), 1439–1459.
[24] J. Lee and C. Spence. 2008. Assessing the benefits of multimodal feedback on dual-task performance under demanding conditions. In *Proceedings of the 22nd British HCI Group Annual Conference on People and Computers: Culture, Creativity, Interaction—Volume 1*. British Computer Society, 185–192.
[25] R. Leung, K. MacLean, M. B. Bertelsen, and M. Saubhasik. 2007. Evaluation of a haptically augmented touchscreen gui elements under congitive load. In *Proceedings of the International Conference on Multimodal Interfaces*. 374–381.
[26] L. E. Magee and J. M. Kennedy. 1980. Exploring pictures tactually. *Nature* 283 (1980), 287–288.
[27] J. Minogue and M. G. Jones. 2006. Haptics in education: Exploring an untapped sensory modality. *Rev. Edu. Res.* 76, 3 (2006), 317–348.
[28] J. Mullenbach, C. Shultz, J. E. Colgate, and A. M. Piper. 2014. Exploring affective communication through variable-friction surface haptics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3963–3972.
[29] S. R. Nyman, M. A. Gosney, and C. R. Victor. 2009. Psychosocial impact of visual impairment in working age adults. *Brit. J. Ophthalmol.* 94 (2009), 1427–1431.
[30] S. O'Modhrain, N. A. Giudice, J. A. Gardner, and G. E. Legge. 2015. Designing media for visually-impaired users of refreshable touch display: Possibilities and pitfalls. *Trans. Haptics* 8, 3 (2015), 248–257.
[31] M. K. Raja. 2011. *The Development and Validation of a New Smartphone Based Non-visual Spatial Interface for Learning Indoor Layouts*. Master's thesis. The University of Maine.
[32] F. A. van Scoy, D. Mclaughlin, J. V. Odom, R. T. Walls, and M. E. Zuppuhaur. 2006. Touching mathematics: A prototype tool for teaching pre-calculus to visually impaired students. *J. Mod. Optics* 53, 9 (2006), 1287–1294.
[33] A. Vinter, V. Fernandes, O. Orlandi, and P. Morgan. 2012. Exploratory procedures of tactile images in visually impaired and blindfolded sighted children: How they relate to their consequent performance in drawing. *Res. Dev. Disabil.* 33 (2012), 1819–1831.
[34] A. Withagen, A. M. L. Kappers, M. P. j. Vervloed, H. Knoors, and L. Verhoeven. 2012. Haptic object matching by blind and sighted adults and children. *ACTA Psychol.* 139 (2012), 261–271.
[35] T. Wolbers, R. L. Klatzky, J. M Loomis, M. G. Wutte, and N. A. Giudice. 2011. Modality-independent coding of spatial layout in the human brain. *Curr. Biol.* 21, 11 (2011), 984–989.
[36] W. Yu and S. A. Brewster. 2003. Evaluation of multimodal graphs for blind people. *Univ. Access Info. Soc.* 2, 2 (2003), 105–124.
[37] W. Yu, K. Kangas, and S. A. Brewster. 2003. Web-based haptic applications for blind people to create virtual graphs. In *Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 318–325.
[38] W. Yu, R. Ranmloll, and S. A. Brewster. 2001. Haptic graphs for blind computer users. *Haptic Human-Computer Interaction* (2001), 41–51.

Received December 2017; revised November 2018; accepted December 2018