Touchscreen-based Haptic Information Access for assisting Blind and Visually-Impaired Users: Perceptual Parameters and Design Guidelines

Hari Prasath Palani[1,2], Jennifer L. Tennison[3], G. Bernard Giudice[2], and Nicholas A. Giudice[1,2]

[1] Spatial Informatics program: School of Computing and Information Science, The University of Maine, Orono ME 04469, USA
[2] VEMI Lab, The University of Maine, Orono ME 04469, USA
[3] Department of Aerospace and Mechanical Engineering, Saint-Louis University, St. Louis MO, USA

`haripras ath.palani@maine.edu`, `jen.tennison@slu.edu`, `bernie.giudice@gmail.com`, `nicholas.giudice@maine.edu`

Abstract. Touchscreen-based smart devices, such as smartphones and tablets, offer great promise for providing blind and visually-impaired (BVI) users with a means for accessing graphics non-visually. However, they also offer novel challenges as they were primarily developed for use as a visual interface. This paper studies key usability parameters governing accurate rendering of haptically-perceivable graphical materials. Three psychophysically-motivated usability studies, incorporating 46 BVI participants, were conducted that identified three key parameters for accurate rendering of vibrotactile lines. Results suggested that the best performance and greatest perceptual salience is obtained with vibrotactile feedback based on: (1) a minimum width of 1mm for detecting lines, (2) a minimum gap of 4mm for discriminating lines rendered parallel to each other, and (3) a minimum angular separation (i.e., cord length) of 4mm for discriminating oriented lines. Findings provide foundational guidelines for converting/rendering visual graphical materials on touchscreen-based interfaces for supporting haptic/vibrotactile information access.

Keywords: Assistive Technology · Haptic information access · Haptic interaction · Multimodal interface · Design Guidelines

1 Introduction

Accessing graphical information is a major challenge for blind and visually-impaired (BVI) individuals. Text-to-speech programs such as JAWS for Windows (www.freedomscientific.com), VoiceOver for iOS-based devices (www.apple.com/accessibility/voiceover), and TalkBack for Android devices (www.google.com/accessibility/), have largely resolved the issue of non-visual access to textual and verbal information. However, there are currently no analogous technologies for providing similar nonvisual access to graphical information. For decades, many researchers, developers, and companies have attempted to resolve this issue, but the solutions that have been developed have made little progress in reaching BVI end-users [1–3]. This is problematic, as a substantial amount of informational content used in educational settings, the workplace, or in myriad everyday activities is presented in graphical formats. Thus, unless new graphical access solutions are developed, more than 12 million BVI people in the U.S. (and 285 million worldwide) will continue to experience negative consequences of this accessibility gap on their educational, vocational, and navigational needs/success [4–6]. A considerable amount of work has been carried out on techniques for converting 2D graphical information, such as graphs and maps, into tangible versions that are developed and rendered using thermoform machines, tactile embossers, force-feedback devices, refreshable haptic displays, surface-haptic displays, tactile-shape displays and vibrotactile displays [7–12]. While these approaches have demonstrated utility in supporting access to graphical content, they also suffer from various shortcomings, such as significant expense, non-portability, and lack of ability to render graphics in a dynamic, real-time context [3, 13, 14].

Advancements in touchscreen-based smart computing devices (such as smartphones and tablets) have transformed the way the BVI demographic interacts with digital information. Most of these touchscreen devices are capable of providing multimodal feedback (i.e., through visual, auditory, and haptic cuing). In supporting universal design principles, most of these devices are also designed with accessibility features as part of the out-of-the box native interface, such as Apple’s VoiceOver and Google’s TalkBack. Owing to these advantages, and the ability to leverage many of these built-in multimodal features to support other tasks, there has been growing interest among researchers and developers in utilizing touchscreen-based smart devices as the core computational platform for providing non-visual graphical access to BVI users. Solutions have been developed based on auditory cues [15–17], vibratory cues [18–20], or combinations of the two [21–23]. Several recent approaches have also utilized electrostatic screen overlays that were coupled with touchscreen devices to generate frictional forces between the contact finger and the screen [24, 25].

These solutions offer great promise as the touchscreen devices underlying this new wave of information-access are widely available at a reasonable cost and are capable of providing portable, refreshable graphical information. While promising, they also come with some inherent non-visual accessibility challenges, as the underlying device was primarily developed for use as an interactive visual display. It is argued here that the haptic feedback capabilities of touchscreen devices are vastly under-utilized. If implemented based on principled knowledge of human perceptual characteristics, as is being studied in the current research, the haptic modality could be a highly effective primary interaction style with these devices for BVI users, as well as for supporting sighted users in eyes-free applications [26]. One of the major challenges with touchscreen-based, non-visual graphical access is that the display is a flat, featureless surface, which does not provide the meaningful cutaneous stimulation that one would receive from apprehending traditional raised tangible graphics. To overcome this limitation, touchscreen-based interactions must rely on extrinsic feedback (e.g., vibration, audio, or electrostatic frictional cues) to indicate contact with an on-screen graphical element. This extrinsic feedback means that it is more difficult to distinguish fine detail and precise spatial information on a touchscreen that would otherwise be easily discernible from physical access using tangible graphics or from visual perception on the same touchscreen display.

For accurate non-visual haptic interpretation of the on-screen rendered graphical elements, users must follow a three-step process: (1) employ proprioception (i.e., force, position and motion sensors) to keep track of their finger position within some frame of reference, defined by the body or external landmarks such as the display frame, (2) extract the spatial information by synchronously interpreting the vibrotactile cues that innervate pacinian corpuscles in the fingertip, and (3) interpret the on-screen stimuli by associating the perceived sensory information with the on-screen graphical element [21, 30]. Because of these differences, graphical materials rendered on touchscreen-based interfaces should be schematized and rendered differently from techniques used for creating traditional tangible graphics. Although several studies have shown initial efficacy of utilizing touchscreen-based devices to address the non-visual graphical accessibility issue [18–20], they have all utilized different parameters for their evaluations. For instance, a ~0.35inch (which is 8 times the size of traditional embossed graphical lines) was utilized as the optimal line width for rendering and accessing shapes, graphs and maps using a *Vibro-Audio Interface* (VAI) on a 7.0inch android galaxy tablet [27, 28]. Similarly, a target size of ~0.17inch (48pixel) was used in the *Timbremap* project for map exploration using an iPhone [16] and a rendering width of ~0.20 inch was used for shape identification in the *GraVVITAS* project, which was based on a Dell Latitude XT touchscreen Tablet [18]. For these alternative non-visual access solutions to succeed, it is crucial that the underlying graphical material is schematized and rendered based on perceptual parameters that are empirically identified to support accurate haptic perception on touchscreen-based displays. Towards this end, this paper conducted three psychophysically-motivated experiments to investigate three key perceptual parameters for detecting on-screen vibrotactile lines (Exp 1), discriminating straight vibrotactile lines (Exp 2) and discriminating oriented vibrotactile lines (Exp 3). The Institutional Review Board (IRB) of the University of Maine approved all three studies and all 46 participants gave informed consent and were paid for their participation.

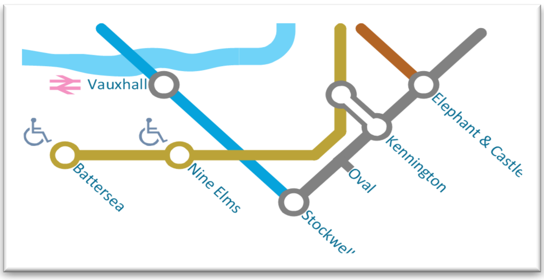

Fig. 1. Sample transit map

2 Experiment 1: Line detection

Lines are a foundational element and a crucial spatial construct for rendering graphical materials such as graphs and maps (see Fig.1. for a sample transit map). The ability to detect distinct lines using vibrotactile feedback is a key process for supporting haptic information extraction on touchscreen-based non-visual interfaces. To support accurate haptic perception and apprehension of the overall graphical information, each vibrotactile line must be rendered at a minimum width that not only supports detection but also preserves the spatial structure and topology of the original visual graphical rendering. Accordingly, experiment 1 was designed to identify the minimum threshold for rendering graphical lines that best supports detection via vibrotactile cuing.

2.1 Method

Twenty blind and visually-impaired participants (nine males and eleven females, ages 27-74) were recruited for the study. Seven different line widths (0.125, 0.25, 0.5, 1, 2, 4, and 8mm) were compared. The seven line widths were chosen to reflect a meaningful range, e.g. the smallest width of 0.125mm is approximately equivalent to the size of a single pixel on most touchscreen displays. From this base, the stimuli increased linearly by a factor of 2 up to 8mm, which is known from empirical studies to be sufficient to perform the three-step process described earlier [27, 28, 31]. The vibrotactile lines were all rendered using an experimental prototype, called a vibro-audio interface (see [27] for technical details and implementation of the VAI), which was implemented on a 5.6inch Galaxy Note4 Edge Android phablet (with a screen resolution of 524 ppi). The vibratory feedback was triggered using Immersion Corp's (www.immersion.com) universal haptic layer (UHL). On-screen contact with the vibrotactile lines triggered constant vibratory feedback based on the UHL effect "Engine1_100" which uses a repeating loop at 250 Hz with 100% power. The study followed a within-subjects design, where each participant performed 84 line counting trials (resulting in 360 observations for each tested line width). In each trial, the randomly generated lines were rendered on the device screen. Participants were asked to move their finger across the screen from left to right at a constant speed, to count the number of vibrotactile lines perceived during this scan and to verbally indicate this number to the experimenter. Participants performed 5 practice trials before performing the 84 experimental trials. Each participant took between 15 and 30 minutes to complete the entire experiment. Based on this design, line detection accuracy was compared between the 7 line widths.

2.2 Results and discussion

A one-way repeated measures ANOVA comparing detection accuracy across the seven tested line widths revealed a statistically significant difference, $F(6, 1526) = 89.913$, $p < 0.001$, $\eta 2 = 0.261$. Subsequent post-hoc t-tests with Bonferroni correction indicated that line widths 0.125, 0.25 and 0.5mm were statistically different in detection accuracy from each other and exhibited significantly lower detection accuracy than the remaining four line widths (all *p*s<0.05). However, there were no statistically significant differences (all *p*s>0.05) observed in detection accuracy between line widths of 1, 2, 4, and 8mm (see Table 1 for means and SDs).

Length (mm)	Mean	SD
0.0125	0.39	0.489
0.25	0.54	0.499
0.5	0.75	0.432
1	0.94	0.237
2	0.93	0.261
4	0.94	0.237
8	0.96	0.188

Table 1. Mean detection accuracy and standard deviation across tested line widths

These results indicate that rendering graphical (vibrotactile) lines at a width of 1mm is sufficient for tasks requiring simple line detection. While adopting a line width wider than 1mm may improve saliency, it will also consume more screen space than necessary. Since touchscreen devices have limited screen real-estate, we argue that adopting wider than a 1mm line width is a poor design decision.

3 Experiment 2: Discrimination of vibrotactile lines rendered parallel to each other

Graphical materials often have multiple lines rendered in close proximity to each other. For instance, consider the transit map depicted in Fig. 1, where there are three different transit lines that make up the actual map. To be recognized as a distinct transit line, each of the lines must be separated from its adjacent line by a gap wider than the minimum perceivable vibrotactile gap width. If the transit lines of this example were to be rendered too close to each other on the touchscreen display, they will be haptically perceived as one line, owing to the sparse spatial resolution of touch. On the other hand, rendering them further apart, using too large of an inter-line gap, is a poor design decision, as it consumes unnecessary screen space on the limited information density displays available on touchscreen-based devices. In addition to the actual gap width, the width of the bounding vibrotactile lines might also influence the perception of the gap. This is because the vibrotactile feedback on touchscreen devices is generated via actuation of an embedded vibratory motor, which has a temporal lag in turning the motor on or off. Any lag due to turning the motor on or off, could in principle, create a spurious perception of a line being narrower or wider than its actual size. Depending on the width of the bounding vibrotactile lines, this spurious haptic perception could mask the gap between them, resulting in the two lines being incorrectly perceived as one. Accordingly, the second experiment was designed to identify the minimal gap width that supports discrimination of two or more vibrotactile lines rendered parallel to each other while also evaluating whether the width of adjacent lines causes spurious haptic perception due to the lag in vibrotactile feedback.

3.1 Method

Eighteen blind and visually-impaired participants (seven males and eleven females, ages 27-74) were recruited for the study. Five gap widths (i.e., 0.25, 0.5, 1, 2, and 4mm) were compared. The gap widths were chosen such that 1mm (as was found in experiment 1) was kept as the median value and increased (or decreased) by a factor of two. The apparatus, implementation, and procedure was similar to that of experiment 1. To assess the effect of temporal lag in triggering vibrotactile feedback and to better characterize and understand the relation of line width on gap detection accuracy, the five gap separations were tested across three different line widths (i.e., 1, 2, and 4mm). A gap trial could have 1, 2, or 3 pairs of lines. The line widths and gap widths were held constant within each trial. To prevent learning effects, 9 dummy trials (i.e., trials where the rendered stimuli did not have gaps) were added to the 45 gap detection trials (5 gaps by 3 line widths by 3 line pairs). In each trial, randomly generated lines were rendered on the screen. Participants were asked to move their finger across the screen from left to right at a constant speed, to count the vibrotactile lines perceived during the scan, and to verbally indicate this count to the experimenter. Participants performed 5 practice trials before performing the 54 experimental trials, which resulted in 324 observations for each tested gap width (i.e., 6 instances for each of the 3 line widths by 18 participants). Each participant took between 20 and 30 minutes to perform the task. Based on this design, the accuracy in gap detection was compared as a function of: (1) gap width (i.e., the space between a pair of parallel vibrotactile lines), and (2) the vibrotactile line width.

3.2 Results and discussion

A one-way repeated measures ANOVA comparing the detection accuracy across the five tested gap widths revealed a statistically significant difference between the gap widths $F(4, 805) = 16.859$, $p < 0.001$, $\eta 2 = 0.077$. Subsequent post-hoc paired sample t-tests with Bonferroni correction indicated that gap widths 0.25 and 0.5mm were statistically different in detection accuracy from each other and exhibited reliably lower detection accuracy than the remaining two gap widths (all *p*s<0.05). Of the tested gap widths, only the 2mm and 4mm gap widths exhibited detection accuracy greater than is required by traditional psychophysical procedures (i.e., 75% detection accuracy [32]). While the trend of these data suggests that further increasing the gap width would likely lead to a corresponding increase in detection accuracy, it will also consume excessive screen real estate and will eventually reduce the efficiency (and practicality) of using touchscreen-based nonvisual graphical access solutions. The results also clearly demonstrate that gap detection accuracy was significantly influenced by the width of the bounding vibrotactile lines, with wider lines exhibiting higher detection rates. On comparing the detection accuracy across the three line widths, a repeated measures ANOVA revealed a statistically significant difference between line widths $F(2, 807) = 31.323$, $p < 0.001$, $\eta 2 = 0.072$. Data here suggest that the detection accuracy increased with an increase in line widths. These findings suggest that gap detection is not only dependent on the width of the gap but also on the width of the bounding lines. We interpret these results as demonstrating that the line and gap width parameters should not be treated separately when creating / authoring vibrotactile graphical information. While exp1 suggested that a 1mm width is sufficient for detection of individual line, the data here suggests that a line width of at least 2mm, in conjunction with an inter-line gap of at least 4mm, should be maintained for distinguishing distinct parallel lines.

4 Experiment 3: Discrimination of Oriented Vibrotactile lines

As stated earlier, with the extrinsic cuing mechanism employed on touchscreen devices, users can only detect whether the touched location is on or off of an on-screen graphical element but they cannot directly perceive any other meaningful information such as stimulus width/length/orientation/angle. To extract this type of information from touchscreen devices, users must perform exploratory procedures (Eps), which are a stereotyped pattern of manual exploration observed when people are asked to learn about a particular object property during voluntary manual exploration without vision [33]. While experiments 1 and 2 indicated the minimum line and gap widths for detection of parallel vibrotactile lines, it is not clear whether these parameters are generalizable to oriented vibrotactile lines and angular graphical elements (For example, see the green and yellow transit lines on Fig. 1.). For identifying such oriented lines and judging the angle subtended between them, users typically employ a 'circling' strategy, where they move their finger in a circular pattern around the intersection as their exploratory procedure [21, 22, 31]. Based on this exploration strategy, we posit here that the arc of the circle formed between two oriented vibrotactile lines will be perceived by the user as the angular magnitude subtended between the two lines. The cord length (and by extension the angular separation between two oriented lines) is a variable that is dependent on both the angle (θ) subtended between oriented lines and the radius (r) of the circle formed by the user while performing their exploratory procedure to apprehend the vertex/intersection of the lines. From a geometric standpoint, the straight-line distance between two angled lines is the cord length (cord length = $2r \sin(\theta/2)$), a variable that depends on: (1) θ - angle subtended between the lines, (2) r – the radius of the traced circle, or (3) both 1 and 2. In theory, the 4mm gap width identified in exp-2 should be translated into a 4mm cord length for accurate detection of distinct oriented lines. However, the cord length can vary depending on the angle, the radius, or both. For instance, an angle of 5° will lead to a 4mm cord length with a 1-inch radius circle, and an angle of 2° will lead to a 4mm cord length with a 2-inch radius circle. Accordingly, experiment 3 was designed to assess the influence of the angle, radius, and cord length on users' ability to discriminate oriented vibrotactile lines.

4.1 Method

Eight blind and visually-impaired participants (three males and five females, ages 25-74) were recruited for the study. The stimulus set was designed as a simple network map where multiple vibrotactile lines were converging to/diverging from an intersection point at the center. The number of lines in each stimuli ranged from 5 to 9 based on Miller's "The Magical Number Seven, Plus or Minus Two" [34]. As stated earlier, the radius was set as a constant value of 1-inch and 2-inch for conditions 1 and 2 respectively. At a radius of 1-inch from the intersection, the minimum gap width of 4mm (i.e., cord length in this context) was translated to an angular magnitude of ~9°. Similarly, at a 2-inch radius, the gap width of 4mm width was translated to a ~5° angular magnitude. To evaluate the influence of cord length (i.e., gap) on the perception of oriented lines, two additional angles (2° and 22°) were also added to the stimulus set that approximately translated to the 4mm gap width at a radius of 0.5-inch and 4-inch (i.e., the radius of the two primary conditions increased and decreased by a factor of 2).

Fig. 2. Experimental device setup with sample experimental stimuli

The stimuli were all rendered using the vibro-audio interface implemented on a 10.1 inch Galaxy Tab 3 Android Tablet (with a screen resolution of 264 ppi). For controlling the circle radius in each condition and for assisting users with the circling strategy, two circular paper stickers of 4mm width (one at 1-inch from the center and the other at 2-inches from the center) were affixed on the screen (see Fig. 2). In addition, the intersection point (center of the screen) was also demarcated with a paper sticker of 10mm radius. To assist participants with orienting themselves on the screen, each circle had a start point (indicated by a tactile marker at the 5 o'clock position). A trial rendered 5, 6, 7, 8, or 9 lines on the screen. In each trial, the angular magnitude between adjacent lines was kept constant irrespective of line number. The order of the conditions (1-inch versus 2-inch radius) was balanced across the participants and the order of stimuli presentation in each condition was randomized. Each participant performed 4 practice trials before performing 28 oriented line counting trials in each condition (resulting in 180 observations for each tested angular magnitude). Each participant took between 20 and 40 minutes to complete the entire experiment. Based on this design, oriented line detection accuracy was compared as a function of 4 angular magnitudes and across 2 circling conditions.

4.2 Results and discussion

A one-way repeated measures ANOVA comparing the line counting accuracy across the four tested angles revealed a statistically significant difference for both circling conditions. The f and p values are as follows,

For the 1-inch circular path, $F(3, 220) = 10.057, p < 0.001$, *For the 2-inch circular path,* $F(3, 220) = 8.574$, $p < 0.001$,

Post-hoc t-tests with Bonferroni correction revealed that the difference in line counting accuracy between observations with a 2° angle compared to the other three angles was significant ($p < 0.001$). However, there were no significant differences between the other three angles (5°, 9°, and 22°). Overall, findings indicate that a 4mm cord length must be maintained to detect/discriminate oriented vibrotactile lines using a circling strategy.

5 Conclusion

Smartphone usage among the BVI demographic has sharply increased in recent years, going from 12% in 2009 to 82% in 2014 [35]. Given the magnitude of this touchscreen device adoption/usage trend among BVI users, it is of utmost importance to investigate and identify the key usability parameters and cognitive abilities pertinent to maximizing accurate use of these interfaces. This paper described three experiments that assessed three key usability parameters for non-visually detecting and discriminating graphical elements using vibrotactile cues on commercial touchscreen interfaces. Overall, results showed that a width of 1mm is sufficient for detecting on-screen graphical elements using vibratory feedback (Exp 1), but a line width of 2mm along with a 4mm inter-line gap must be maintained for accurate detection and discrimination of distinct vibrotactile lines that are parallel to each other (Exp 2). Similarly, experiment 3 suggested that a 4mm cord length (similar to the 4mm gap width) must be maintained for accurate detection and discrimination of oriented vibrotactile lines. It is important to consider that these parameters are not just based on cutaneous sensation but represent the value at which a user can effectively perform the three-step process of employing proprioception to keep track of their finger position within some frame of reference, extracting the spatial information by synchronously interpreting the vibrotactile cues, and associating the perceived sensory information with on-screen graphical elements.

This work adds to the growing corpus of research demonstrating the efficacy of these interfaces as the latest category of information-access technology. To best utilize this technological trend, findings from this work provide much-needed foundational guidelines for converting/rendering visual graphical elements on touchscreen-based interfaces for supporting haptic information access. These findings, along with other work in this domain, are the first step towards development of a set of robust design guidelines to provide improved haptic access on touchscreen devices supporting a wide range of non-visual applications.

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