Summer 8-17-2018

Principles and Guidelines for Advancement of Touchscreen-Based Non-visual Access to 2D Spatial Information

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PRINCIPLES AND GUIDELINES FOR ADVANCEMENT OF TOUCHSCREEN-BASED NON-VISUAL ACCESS TO 2D SPATIAL INFORMATION

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A DISSERTATION

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

(in Spatial Information Science and Engineering)

The Graduate School

The University of Maine

May, 2018

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An Abstract of the Dissertation Presented
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Graphical materials such as graphs and maps are often inaccessible to millions of blind and visually-impaired (BVI) people, which negatively impacts their educational prospects, ability to travel, and vocational opportunities. To address this longstanding issue, a three-phase research program was conducted that builds on and extends previous work establishing touchscreen-based haptic cuing as a viable alternative for conveying digital graphics to BVI users. Although promising, this approach poses unique challenges that can only be addressed by schematizing the underlying graphical information based on perceptual and spatio-cognitive characteristics pertinent to touchscreen-based haptic access. Towards this end, this dissertation empirically identified a set of design parameters and guidelines through a logical progression of seven experiments.

Phase I investigated perceptual characteristics related to touchscreen-based graphical access using vibrotactile stimuli, with results establishing three core perceptual guidelines: (1) a minimum line width of 1mm should be maintained for accurate line-detection (Exp-1), (2) a minimum interline gap of 4mm should be used for accurate discrimination of parallel vibrotactile lines (Exp-2), and (3) a minimum angular separation of 4mm should be used for accurate discrimination of oriented vibrotactile lines (Exp-3). Building on these parameters, Phase II studied the core spatio-cognitive characteristics pertinent to

touchscreen-based non-visual learning of graphical information, with results leading to the specification of three design guidelines: (1) a minimum width of 4mm should be used for supporting tasks that require tracing of vibrotactile lines and judging their orientation (Exp-4), (2) a minimum width of 4mm should be maintained for accurate line tracing and learning of complex spatial path patterns (Exp-5), and (3) vibrotactile feedback should be used as a guiding cue to support the most accurate line tracing performance (Exp-6). Finally, Phase III demonstrated that schematizing line-based maps based on these design guidelines leads to development of an accurate cognitive map. Results from Experiment-7 provide theoretical evidence in support of learning from vision and touch as leading to the development of functionally equivalent amodal spatial representations in memory. Findings from all seven experiments contribute to new theories of haptic information processing that can guide the development of new touchscreen-based non-visual graphical access solutions.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, mentor, and friend Dr. Nicholas A. Giudice for his support and patience throughout this work. He is an inspiration who taught me several professional and life skills that will stay with me as I continue my career. Without his timely support and irreplaceable advices, it would have been impossible to perform this dissertation research.

I want to thank my committee members Kate Beard-Tisdale, Silvia Nittel, Shawn W. Ell, Max Egenhofer, and Nimesha Ranasinghe. The knowledge I gained from your courses and personal interactions helped guide my work. I greatly appreciate all the support and advice and I want to thank you for all the time you have spent reviewing my dissertation work.

Special thanks to VEMI Lab Director Dr. Richard Corey and Lab Manager Raymond J Perry. Over the years they have helped me with several aspects towards the progression of the research. I would like to extend my gratitude to every, past and present, member of the lab who has helped me develop as an academic and person in some way. In particular, I want to thank Dr. Hengshan Li and Dr. Christopher Bennett for shaping my research as a fellow researcher and shaping me personally as a good friend.

I would also like to thank all my friends at the University of Maine for their support. I particularly want to thank, Phaneendra Chennampally, Shirly Stephen, Praveen Gunturi, and Sudheera Yaparatne for providing me with a shelter and feeding me during my Orono visits. I would also like to acknowledge the support from NIDRR, NSF, and NIH that made all of my work possible and supported me financially.

I would also to my parents, friends, and family for their unwavering support in all of my endeavors.

Lastly, but certainly not the least, Saranya Kesavan, my wife. The bedrock of my life that made all this work possible. I cannot thank you enough for your patience, understanding, and encouragement over the years. No words can truly match my thanks to you and so I dedicate this dissertation to you.

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1. INTRODUCTION

1.1 Motivation

Graphical materials such as graphs, charts, maps, mathematical drawings, etc., represent a key medium of information exchange in educational settings, for navigation, the workplace, or in the myriad of life's everyday activities. Accessing and interpreting such graphical materials is extremely important, as much of this information is crucial for independent living, employment, education, and safe navigation [Banovic et al. 2013; Smiciklas 2012]. Unfortunately, the visual nature of such graphical materials prevents millions of blind and visually-impaired (BVI) people from accessing this wealth of critical information. While Braille displays and screen reading software using text-to-speech engines such as VoiceOver for Mac/iOS (www.apple.com/accessibility/) and JAWS for Windows (www.freedomscientific.com), have largely solved the issue of providing access to text-based materials, there are no analogous solutions for providing non-visual access to graphical materials. The BVI demographic is estimated to number around 12 million people in the U.S. and 285 million people worldwide [World Health Organization 2011]. Unless new non-visual graphical access solutions are developed, lack of access to this wealth of graphical information will continue to have negative consequences on the educational, vocational, navigational, and social needs of the BVI demographic [Giudice et al. 2012; Palani 2013]. To better appreciate the graphical accessibility issues faced by millions of blind and visually-impaired people, the reader is encouraged to visualize the following real-life scenario of a representative blind person - *Cody*. The following is a consolidation of stories (and situations) reported to me by 128 people during in-person interviews conducted as part of NSF's I-Corp program, which was performed as part of this dissertation research. The interviews were conducted across the country with the target BVI demographic and their broader eco-system including teachers of visually-impaired students (TVIs), parents of blind children, assistive technology trainers, orientation and mobility (O&M) trainers, and several others involved in blindness accessibility.

"Hi, I am Cody. I am from Florida. I was born blind and was brought up in a supportive family that encouraged me to be independent and explorative. I am very adventurous and I like exploring new places. During my primary school training, I had a dedicated aid appointed by my school for helping me to get accessible course materials. In addition to her, I also had a specialized teacher (i.e., teacher of the visually-impaired (TVI)) and Orientation and Mobility (O&M) instructor assigned to me by the state disability services agency. My TVI taught me how to read Braille and my O&M instructor trained me to safely navigate using the long cane and self-localization. My school aid used to create Brailled text materials. She used puff papers to create graphical content that are not very detailed but I at least got to feel around on the tactile output and extract shapes and patterns. As I moved on to higher grades, it became a lot harder for me to get the materials on time as I did not have a dedicated aid. My TVI only use to meet me once a week (or bi-weekly) and would coordinate with my classroom teacher to get me accessible materials. Most of the time worksheets for Science or Math classes were not made accessible in time and as a result, I often ended up raising my hand saying I did not get the material. This was not only awkward for me but it also forced me to fall behind on the class. Most of my classes were based on Powerpoint presentations showing things like the structure of a bacteria cell or a bar graph, which I had no clue how to learn or understand as I did not have a real-time means of accessing them. Compared with my sighted peers, I started missing out a lot in the class and I was also forced to do makeup work, with the delay depending on when I got the materials in an accessible format. I had to deal with these information access problems on a daily basis and it kept getting worse as I advanced in grades and was exposed to more complicated material. Although I liked Math and Science initially, I started losing interest because of the hardships in getting accessible materials to pass those courses. This was not the case with other courses as I was able to access text using different OCR (optical character

recognition) devices, screen-reading software (e.g., JAWS) and Braille materials. Since I had timely access of these materials, I was able to excel in English and gradually started acquiring an interest towards History and eventually chose this to be my major.

I attended a private college in Florida to do my Bachelor's degree, majoring in History with a focus on southern history. Being a history major, I had to go to a lot of Museums but getting there was always a challenge. I used google maps to get step-by-step walking directions but in many instances, it led me only to the corner of the building and I had to then ask someone to guide me to the entrance. I like to be prepared for my journey and know where I am going but there is no way for me to access the global structure of that area as none of the maps that my friends use on their smart phones are accessible to me. Arriving at my destination always involves trial and error through my routing app and self-localization process or relying on others to guide me. This trouble continues even after I enter the museum as the layout and positioning of the artifacts within the museum are completely inaccessible. I have to rely on someone to point me in the right direction or guide me within the environment. This is the same situation whenever I go to a new shopping mall or travel through an Airport. Most times I would reach the airport early and even if I want to get a coffee or go to the restroom, I have to ask directions from somebody or get help from a skycap member. If I can get access to the layout of the museum or the airport either before traveling or at the location, I would not need to rely on someone. I can use my O&M and self-localization skills to find my way within those environments. But currently there is no way for me to get access to the same map information that my sighted friends seem to use without thought or concern."

Cody's accessibility issues in navigational, educational, and subsequent vocational settings are shared among millions of other BVI people, who are either congenitally blind (blind from birth) or late blind due to accidents, eye-related diseases, or aging. Just like Cody, most of the BVI students we interviewed,

corroborated by the literature [Erickson et al. 2010; National Federation of the Blind 2017], tend to deviate from STEM (Science, Technology, Engineering, and Mathematics) disciplines. This is because exceling in STEM curricula requires substantial access to graphical information such as graphs, diagrams, images, flowcharts, and engineering designs. This lack of graphical information access is more than a mere frustration, as it negatively impacts BVI people in their educational prospects i.e., only ~11% have a bachelor's degree [Erickson et al. 2010], ability to travel i.e., 30% do not travel independently outside of their home [Clark-Carter et al. 1986], and for employment i.e., more than 70% are unemployed [Kaye et al. 2000]. It is argued here that these troubling issues could be greatly improved by developing a viable solution that provides real-time non-visual access to visual graphical information. Gaining a deeper scientific understanding of this overarching problem and addressing it through development and evaluation of a viable graphical access solution are the core motivations of this doctoral thesis.

1.2 Introduction to Non-Visual Graphical Access

Work on tactile graphics (i.e., graphics that are discernable by the sense of touch) dates back more than a century, and researchers in the ensuing years have devoted considerable effort to their design, development, techniques, and production [Rowell and Ungar 2003a; Rowell and Ungar 2003b; Perkins 2015]. Of note, paper-based tactile maps are the most frequently used approach, followed by refreshable haptic displays. Some notable solutions include: the camera-based Optacon, which used an electrotactile display [Bliss et al. 1970]; force-feedback devices such as PHANTOM devices [Phantom 2015]; tactile pin-based displays, such as the HAPTAC and Virtouch mouse [Hasser 1995; Kammermeier and Schmidt 2002]; and static hardcopy embossers such as the Viewplus emprint and Ink Pro, equipped with Tiger embossing Technology that supports preparation of static tactile graphics using pin-matrix embossers with a higher resolution of about 20 dpi and eight different height levels for embossed dots [ViewPlus 2018]. A detailed survey of several non-visual graphical access solutions is provided in section 2.1. While there are pros and cons of all extant non-visual solutions, they have enjoyed only limited

success in real-world adoption and usage due to various shortcomings, such as their single-purpose nature, non-portability, use of unintuitive sensory translation rules, significant expense (i.e., typically in the price range of $5,000 for a braille embosser to $50,000 for a full page Braille display), steep learning curve, poor added value compared to other well-accepted sensory aids, lack of ability to render graphics in a dynamic setting, and limited commercial availability [O'Modhrain et al. 2015; Samuelson and Zeckhauser 1988; Elli et al. 2014]. These shortcomings have greatly limited these solutions from addressing the underlying graphical access problem and by extension reaching the BVI demographic.

It should be noted that the host of aforementioned shortcomings and challenges relate to three unresolved research domains: (1) some are due to lack (or improper implementation) of basic theoretical knowledge about perceptual and cognitive factors involved in non-visual information processing, (2) some are due to a dearth of usability research in optimizing the information content provided or the user interface developed, and (3) some are due to what is termed the "engineering trap", which occurs when design is driven by engineering principles or by the technology itself, rather than being motivated by relevant perceptual or cognitive factors associated with the technology and the user needs/tasks it is meant to support [Giudice and Legge 2008]. For instance, the HyperBraille is the most advanced tactile graphics display currently available, but it costs approximately $56,000, putting it far beyond the reach of the vast majority of BVI end-users. Subsequently, the focus of the research field shifted from usability aspects to engineering aspects since the primarily goal was to reduce the cost. Products such as the Virtouch mouse (that uses one or two Braille cells coupled with a commercial mouse) tackled the cost but failed to address the usability. Subsequently blind users found it difficult to use and by extension the product failed to address the overarching problem of non-visual graphical accessibility. It is postulated here that the underlying issue of non-visual graphical accessibility primarily stems from the disconnect between these three aforementioned research domains. For a non-visual

access solution to be truly useful and broadly accepted, it is necessary to approach the issue with an interdisciplinary outlook bridging:

(1) ***Foundational theoretical research*** that focuses on touch perception, sensory substitution, and theories from spatial science.

(2) ***Technological research*** that emphasises interface/product design, multimodal interaction design, and Human-Computer Interaction design.

(3) ***Usability research*** that evaluates user acceptance, behavior, efficacy, advantages/disadvantages, and generalizability of a new interface/product/approach.

Accordingly, this dissertation research aims to integrate these three often disparate domains under the unified goal of addressing the non-visual graphical access issue. Connecting these three disciplines also paved the way for development of a novel and viable graphical access solution.

1.2.1 Introduction to Haptic Information Access on Touchscreen Devices

Advancements in touchscreen-based computing devices such as smartphones and tablets have amplified our reliance on digital information. These devices have opened the door to development of a new era of multimodal interfaces incorporating combinations of auditory, vibro-tactile, and kinesthetic feedback. Unlike the aforementioned tangible graphic solutions (e.g., BrailleDis, Virtouch, GWP, and DotView), touchscreen devices overcome several inherent shortcomings of existing non-visual information access technologies, as they: (1) are affordable at a low-cost (i.e., use of commercial hardware vs. highly specialized adaptive equipment), (2) are built on portable platforms that can be used in many contexts (unlike the large and non-portable traditional hardware), (3) are multi-purposed (i.e., the underlying hardware can be used for other applications), and (4) support modern universal design principles (i.e., the user interface is highly customizable and includes many embedded accessibility features in the native OS, such as Apple's Voiceover or Google's TalkBack). As a result of

these key advantages, touchscreen device usage among the visually impaired population has gone up dramatically from 12% in 2009 to 82% in 2014 [WebAim 2017]. However, this increased usage of touchscreen devices remains limited to the reading of textual elements and a nominal ability to enter text. This is problematic as with the general trend of information access, a substantial portion of information content rendered on touchscreen-based devices is being conveyed in graphical formats such as through maps, graphs, scientific simulations, video games, and drawings. Thus, despite their many advantages, blind and visually impaired (BVI) people still cannot access such digital graphical information on current touchscreen-based solutions. Consequently, there has been growing interest among researchers and developers in supporting BVI users with access to digital graphical materials utilizing touchscreen devices as the computational platform (see chapter 2 for more details). Some notable approaches include: audio-based approaches [Su et al. 2010; Owens and Brewster 2011; Williamson et al. 2011], vibration-based approaches [Giudice et al. 2012; Goncu and Marriott 2011; Palani 2013; Tennison and Gorlewicz 2016], or combinations of the two [Palani and Giudice 2014; Gershon et al. 2016; Klatzky et al. 2014]. Several recent approaches have also utilized electro-static screen overlays that were coupled with touchscreen devices to generate a frictional force between the contact finger and the screen [Mullenbach et al. 2014; Xu et al. 2011]. While these approaches are promising, they also poses unique and novel challenges due to the limitations imposed by: (1) lack of foundational theoretical research on touchscreen-based haptic perception and spatial cognition, (2) lack of usability research on touchscreen-based non-visual learning of graphical information and subsequent user behaviors, and (3) lack of technological research evaluating the hardware/software limitations in the context of non-visual graphical accessibility. As stated earlier, this dissertation aimed to address each of these challenges via an interdisciplinary and multi-pronged approach incorporating both basic and applied contributions to each of the three research domains (i.e., foundational, usability, and technological).

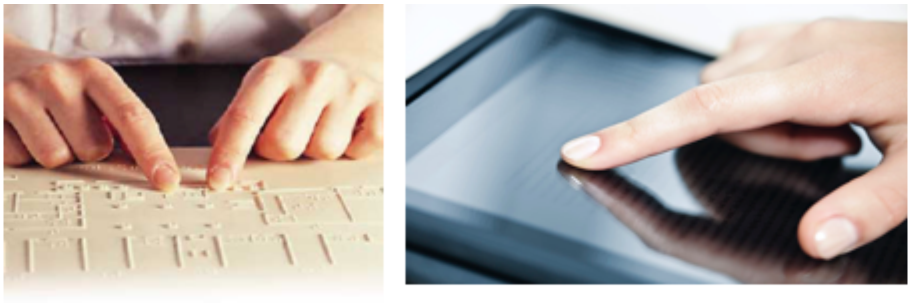

Figure 1.1. Difference between tactile media and touchscreen displays

Although termed as a 'touch display', the tactual component of touchscreen-based interfaces is almost exclusively limited to input. The information output from these displays is primarily visual, or less frequently from audio. With physical tangible media, users can directly touch and perceive the information, with changes in force, friction, and pressure during finger/hand movement leading to skin deformation that innervates *mechanoreceptors* on the fingertip upon contact with the graphical information [Johnson and Philips 1981]. By contrast, with a touchscreen-based non-visual interface, the user can only perceive a flat, featureless glass screen that conveys no meaningful tactual information / cutaneous reinforcement, as the onscreen information does not possess any physical attributes that are directly perceivable by the finger (see Figure 1.1). This means that the stimuli (i.e., an on-screen rendered line diagram) in isolation does not provide any intrinsic cutaneous cues as one would receive from physical pressure-based raised line diagrams. To overcome this absence of intrinsic tactile cues and to facilitate access to on-screen graphical elements, extrinsic feedback (e.g., vibration, friction, or electrostatic cues) must be imposed for supporting accurate perception via touchscreen-based haptic interactions. Earlier work from my Masters thesis [Palani 2013] and other VEMI-based research [Giudice et al. 2012; Raja 2011] led to the development and preliminary evaluation of a novel touchscreen-based multimodal interface, called a *vibro-audio interface* (VAI). The VAI allows for users to freely explore on-screen graphical information without the need for vision, using the in-built vibration and auditory features of any commercial touchscreen device equipped with an audio facility and vibration motor or

haptic engine [Giudice et al. 2012; Palani 2013]. Since touchscreen devices are equipped with only one vibration motor, whenever a user "touches" an onscreen graphical element, the device's vibration motor is triggered, thereby providing immediate focal vibrotactile feedback on the user's finger. The result is that this focal vibration is perceived as feeling the graphical element on the screen. While such extrinsic feedback can indicate contact with graphical elements, the feedback in isolation does not provide any meaningful tactual information such as the width / length of an element. Understanding these fundamental differences in the perceptual process involved in extraction of graphical information via the touchscreen is crucial for developing a viable touchscreen-based graphical access solution (Chapter 2 details the sensory differences between traditional tactile approaches and touchscreen-based approaches).

The challenge of perceptual differences is further aggravated by technical limitations imposed by the underlying hardware. Touchscreen displays are based on a pixel coordinate system where the resolution and pixel size is defined by the density and arrangement of the sensors in the underlying LCD display (see Figure 1.2). Although the finger-pad covers a certain area on the display (i.e., more than one pixel), the device computes and narrows the contact area down to a single pixel (i.e., centroid of the contact area). The extrinsic cuing (i.e., activation of vibration or auditory feedback) occurs based on whether or not this centroid pixel overlaps with the pixels of the on-screen rendered graphical element.

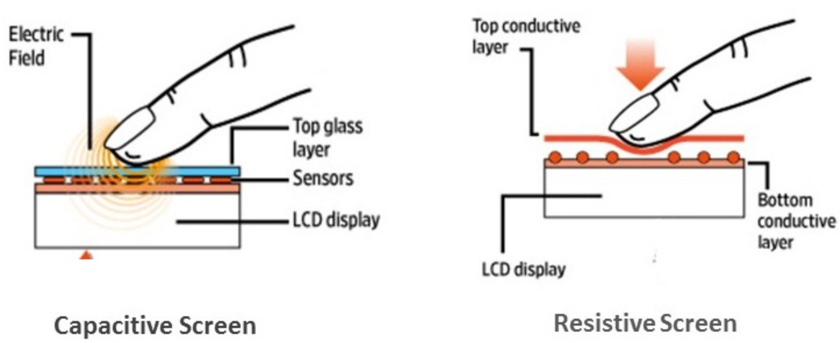

Figure 1.2. How touchscreen displays respond to human touch

Unlike tangible media (see Figure 1.1) where a user can detect the stimuli with any part of the finger's contact area, with touchscreen haptic interactions, the user will be able to detect the stimuli only when the centroid of their finger's contact area overlaps with a pixel of the rendered stimuli. This means that users must employ active finger movements and proprioception even for detecting simple information such as the width of a line and other basic feature attributes. As a result, it is much more difficult to distinguish fine detail and precise spatial information using vibrotactile stimulation from a touchscreen that would otherwise be easily discernible from physical access using tangible graphics or from visual access to the same graphical information rendered on touchscreen displays. For accurate non-visual interpretation of the graphical information via touchscreen displays, 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 an external reference such as the display frame, (2) extract the spatial information by synchronously interpreting the extrinsic cues, and (3) interpret the on-screen stimuli by associating the perceived sensory information with the on-screen graphical element [Klatzky et al. 2014]. Each of these three steps present challenges with respect to: (1) perception: ensuring accurate haptic information extraction, (2) cognition: developing accurate mental representations of the perceived information, and (3) behavior: enabling the developed mental representation to support accurate spatial behaviors.

1.2.2 Research Goals and Scope

The three aforementioned challenges (i.e., relating to perception, cognition, and behavior) serve as a guide for motivating the three research goals at the heart of this dissertation, namely:

(1) to investigate and establish rendering parameters based on perceptual characteristics pertinent to vibrotactile information access on touchscreen interfaces,

(2) to investigate and establish design guidelines based on spatio-cognitive characteristics pertinent to vibrotactile information access on touchscreen interfaces, and

(3) to evaluate and validate the usability of the guidelines established from 1 & 2 in supporting accurate nonvisual learning and subsequent spatial behaviors.

There is dearth of research on touchscreen-based non-visual interactions and as such investigation of these three goals is a previously unstudied area of research. The intent of this dissertation research is not to cover all aspects of this new research area but to perform scientific inquiry on the most relevant aspects. This requires streamlining of the research focus to a core feature of the underlying graphical information. Also, it is important that the investigation and its relevant findings serve as an initial starting point for building future research in this area. Accordingly, the investigation of the three goals was streamlined to focus primarily on the rectilinear line (and polyline) features of graphical materials (e.g., bar graphs, line graphs, subway/metro maps, electrical circuits, etc.,). This is because lines are a foundational element and a crucial spatial construct for rendering graphical materials such as graphs and maps. The rationale for this specification and research focus is not only to reduce the state space of the underlying graphical information evaluated in this dissertation but also to illuminate characteristics of a core graphical component that can serve as a building block for extending the investigation to other components such as regions (e.g., states or provinces in a map where the boundary is indicated as a line). It should also be noted that all types of graphical materials are thought to be formed by a combination of only three types of geometry, namely: point, line, and region [Freundschuh 1997]. Although lines are typically considered as a one-dimensional feature from a formal geometric stand-point and for use in geographic information systems (GIS) [Wegener 1999], when rendered on a touchscreen display, lines are inherently a 2-dimensional object (i.e., comprised of a width and a length) and can be considered a region. To avoid confusion and to clarify its meaning in the context of the current evaluations, *lines* are defined as any on-screen rendered graphical component that represents a linear information such as bars on a bar graph, lines on a line graph, corridors on a building layout, etc.

1.3 Research Phases, Questions and Contributions

The three goals and their related challenges were evaluated and addressed in this dissertation research through a logical progression of three research phases, as presented in Figure 1.3.

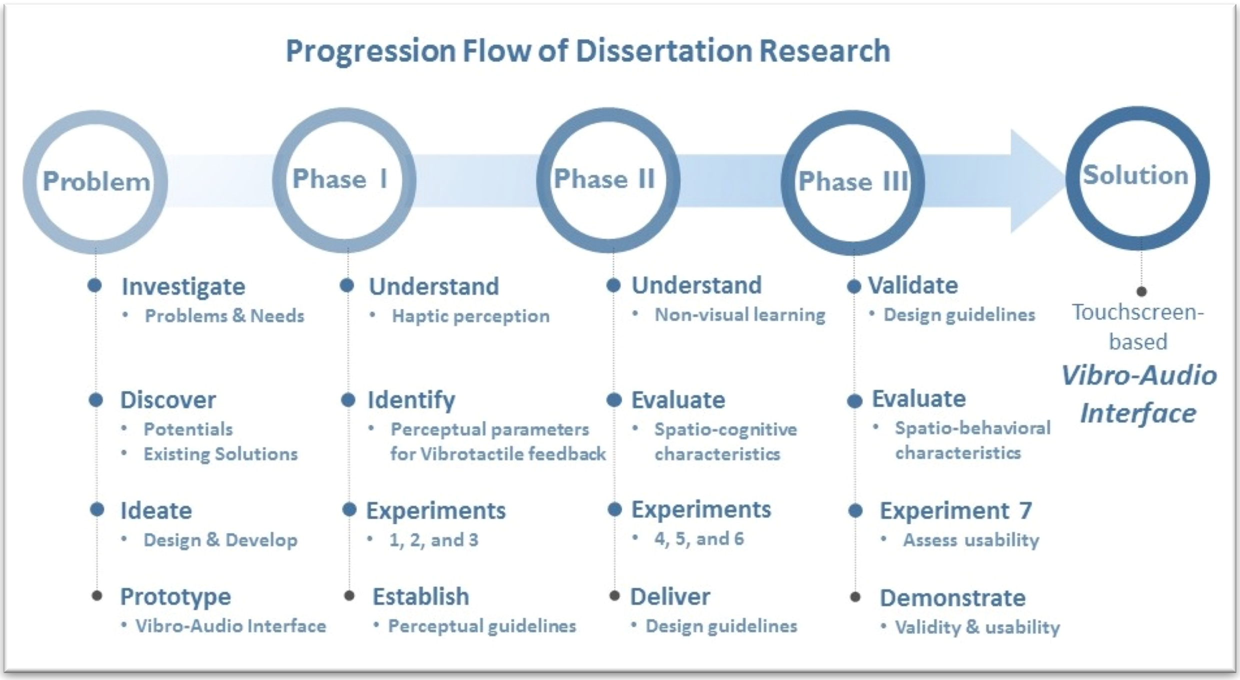

Figure 1.3. Progression flow of this dissertation research

1.3.1 Phase I: Identification of Perceptual Parameters

To tackle the differences imposed by haptic information extraction (as discussed in Section 1.2.2) and to develop truly useful touchscreen-based haptic applications, this dissertation established a set of core perceptual parameters to govern visual-to-haptic conversion of graphical information that goes beyond the naïve technique of simply trying to implement a one-to-one haptic analog of the visual graphical rendering. Since vision is estimated to have 500 times greater sensory bandwidth than touch [Loomis et al. 2012], simply substituting haptic cues for visual cues to extract onscreen information will not be meaningful to users unless the presented information is schematized based on: (1) the perceptual specificity of touchscreen-based vibrotactile feedback, and (2) the technical limitations of the interface that demands active exploration using just one finger for information extraction. Significant efforts have

been made in identifying various perceptual and usability parameters that must be considered for rendering visual elements on touchscreen displays. For instance, the MIT Touch Lab suggests use of a 0.4 to 0.55 inch touch target size for rendering visual buttons on touchscreen displays in order to facilitate precise localization through touch [Ng et al. 2011; Mi et al. 2013; Wroblewski 2010]. This guidance, however, assumes simultaneous visual feedback and it is not clear if the same specifications hold for purely haptic, eyes-free interactions. Similarly, several standards and guidelines have been established for producing tangible graphics using Braille embossers, microcapsule, and even for custom handmade graphics [Braille Authority of North America 2010]. While these guidelines support designing of perceptually-salient tangible graphics that are perceived via pressure-based mechanoreceptors, they cannot ensure saliency when adopted for rendering digital graphical elements via vibrotactile stimulation on touchscreen interfaces (see details in section 2.3). To date, no work to our knowledge, has investigated or identified such parameters for converting or designing graphical materials that are optimized for touchscreen-based haptic perception. Phase I of this dissertation fills this gap in the literature by investigating key perceptual parameters that will serve as a set of much-needed de-facto guidelines specifying the parameters for rendering graphical information supporting accurate haptic perception on touchscreen devices. The following three research questions motivated the efforts of the Phase I research, namely:

1. *What is the minimum width that best supports accurate vibrotactile line detection?*
2. *What is the minimum interline gap that best supports accurate detection and discrimination of parallel vibrotactile lines?*
3. *What is the minimum interline gap that best supports detection and discrimination of oriented vibrotactile lines?*

These three questions focus on identifying three key perceptual parameters that are essential for detection and comprehension of line-based graphical information via vibrotactile cuing on touchscreen

devices. A key argument advanced here is that understanding the limitations of human haptic perceptual capabilities will lead to better schematization and conversion of visual graphical renderings into haptically perceivable graphical renderings. Accordingly, three psychophysically-motivated usability experiments (Exps 1-3) were conducted to empirically determine three core perceptual parameters for rendering haptically perceivable graphical lines on touchscreen interfaces (see Chapter 3 for details).

1.3.2 Phase II: Evaluation of Spatio-Cognitive Characteristics

The three perceptual parameters identified from Exps 1-3 serve as the basis for conversion and schematization of graphical rendering that are haptically perceivable on touchscreen devices. However, even when the graphical renderings are haptically perceivable, various other challenges may arise due to the spatio-cognitive characteristics involved in haptic access of graphical information on touchscreen devices. Challenges arise in terms of spatial resolution, temporal integration, spatial localization, and vulnerability to systematic distortions [Klatzky et al. 2014; Lederman and Klatzky 2009]. With tangible media, users typically employ at least three principle exploratory procedures (EPs) for accessing and extracting graphical information, namely: (1) lateral motion (moving the fingers back and forth across a texture or feature), (2) contour following (tracing an edge within the graphic), and (3) whole-hand exploration of global shape [O'Modhrain et al. 2015; Jones and Lederman 2006; Loomis 1981; Loomis and Lederman 1986; Lederman and Klatzky 1987]. These procedures are highly cognitively demanding, as the spatial information must be integrated across space and time during prolonged tactual exploration. In addition, this information integration is not always precise, which further complicates the development of accurate mental spatial images [Wijntjes et al. 2008].

In addition to the challenges introduced by tactual learning and its inherent perceptual challenges (Phase I), users must overcome two other spatio-cognitive challenges with touchscreens: (1) perform exploratory procedures (*EP*) using just one finger to identify graphical elements, and (2) integrate the perceived graphical elements by synchronously relating spatial information to develop a coherent

mental representation that accurately replicates the global structure of the perceived graphical information. To better conceptualize this issue, try looking at graphical elements of a map through a narrow viewing aperture that matches the size of one of your finger digits and explore it with the intent of comprehending its global spatial structure. With such restricted access, one must constantly integrate the graphical elements across space and time during their prolonged exploration. Even with direct visual cues, this challenging spatiotemporal integration process will likely significantly increase the cognitive effort required to apprehend the global spatial information. This challenge is further aggravated with touchscreen-based non-visual solutions as the information extraction is based on non-cutaneous extrinsic feedback (i.e., vibration). Given these challenges, it is unclear whether this new form of information access technology will support development of an accurate mental spatial image of the presented graphical information. Towards this end, Phase II of this dissertation systematically evaluates the spatio-cognitive challenges involved in touchscreen-based haptic information access and in doing so, simultaneously determines the rendering parameters that best support development of an accurate mental spatial image of the presented graphical information. The following three research questions motivate the Phase II research efforts,

1. *What is the minimum vibrotactile line width that supports line tracing and orientation judgments of onscreen rendered vibrotactile lines?*
2. *What is the minimum vibrotactile line width that supports development of an accurate mental spatial image of complex spatial path patterns?*
3. *Whether vibration should be presented as a guiding cue or as a warning cue for supporting tactual learning on touchscreen-based haptic interfaces?*

These three research questions focus not only on users' perceptual ability but also evaluates their ability to build a mental spatial image of the graphical information perceived via haptic access on touchscreen

devices. The questions were evaluated through three psychophysically-motivated usability experiments 4, 5, and 6 (see Chapter 4 for details). Consolidating the findings from these experiments with the perceptual parameters established in Phase I, a set of empirically valid design guidelines were established for advancing touchscreen-based haptic information access.

1.3.3 Phase III: Evaluation of Spatio-Behavioral Characteristics

The established guidelines from Phase I and II are valid for perceptual and subsequent spatio-cognitive tasks (e.g., identifying orientations and patterns) but are not generalizable for supporting spatio-behavioral tasks. For the findings to be generalizable it is necessary to validate and evaluate their usability in supporting users spatio-behavioral tasks such as wayfinding and allocentric pointing that involve computation, rotation, and inferencing of the developed mental representation (i.e., cognitive map). For the vibro-audio interface evaluated in this dissertation to be truly useful, it is necessary that non-visual learning and subsequent development of cognitive maps support users with spatio-behavioral tasks, in a functionally similar manner to that of accessing visually-based graphics by sighted users or accessing tangible graphics by BVI users. It is hypothesized here that, once the graphical elements are schematized and rendered in accordance with the established guidelines, the vibro-audio solution should, in theory, support accurate non-visual learning of graphical elements in a functionally similar manner as that of well-established approaches. To evaluate this hypothesis, Phase III of this dissertation compared the vibro-audio interface with two well-established graphic access approaches (i.e., a visual touchscreen interface and a non-visual hardcopy tangible interface) for its ability to support spatio-behavioral tasks, such as wayfinding, allocentric orientation, and map reconstruction. Accordingly, the third phase of this dissertation research was designed with a two-fold objective: (1) to validate the established parameters from the Phase I and II research by evaluating its usability to support spatio-behavioral tasks, and (2) to evaluate whether learning via this new form of information access technology leads to development of an accurate cognitive map that is functionally equivalent to

that of well-established hardcopy tangible graphics and visual graphics. The general research question for this phase can be formulated as follows:

Does the approach of using schematized graphical information on the vibro-audio interface lead to development of an accurate cognitive map that is functionally equivalent to those formed from other well-established modes of graphical access?

This question was evaluated through a human behavioral experiment (Exp 7) focused on usability, spatio-temporal integration, spatial-cognition, and spatial behavior (e.g. wayfinding, allocentric pointing, etc.). Chapter 5 describes the full rationale and methods for experiment 7. Findings from this experiment led to validation of the established guidelines and demonstrated its usability for implementation on the touchscreen-based non-visual graphic access solution such as vibro-audio interface advanced here (see Chapter 5 for details).

1.3.4 Contributions

The three major contributions of this thesis are as follows.

1. A core set of design guidelines for schematizing, converting (visual-to-haptic), and rendering of graphical lines that are perceptually-salient and cognitively-valid for vibrotactile access on touchscreen-based interfaces.

2. New insights and knowledge supporting theories on haptic perception, spatial cognition, multimodal information access, and touchscreen-based non-visual graphical access.

3. Development of a viable and novel touchscreen-based graphical access solution and empirical validation that it is functionally equivalent to that of well-established approaches.

The foundational theories on perceptual, spatio-cognitive, and spatio-behavioral insight pertinent to haptic information access and processing that are elucidated by this research contribute significant

knowledge to the domain of spatial information science, especially for researchers involved in non-visual spatial information processing. The findings are highly relevant to researchers, designers, content developers and industries involved in accessibility and Assistive Technology (AT) design. The findings are also important for a much larger user group of sighted people in applications where visual perception is not possible (e.g., glare and smoke) or needed elsewhere (e.g., operating in-car control elements while driving). This research opens the door to a new style of haptic interaction for sighted users and information delivery supporting multitasking and a host of eyes-free applications due to situationally induced impairments and disabilities (SIID). Similarly, the results are relevant to use by older adults who are disproportionately impacted by visual impairments but who often have remaining sensory capabilities and who could also utilize haptic feedback to access information as demonstrated in this work. Given the huge base of touchscreen usage (~ 2.8 billion touchscreen panels were shipped in 2016 alone [Statista 2017]), the guidelines and parameters established in this work will certainly enhance the overall usability of touchscreen-based devices. These contributions have broad societal impact and promote empowerment of BVI individuals through supporting increased educational advancement, vocational opportunities, enhanced quality of life, and overall greater independence.

1.4 Structure of the Thesis

Chapter 2 reviews existing work relevant to non-visual graphical access and lays out the theoretical and practical foundations for touchscreen-based graphical access via vibrotactile feedback.

Chapter 3 discusses the experimental methods and findings for the first three psychophysically-motivated usability experiments (Exps 1-3) conducted as part of Phase I of this dissertation research.

Chapter 4 describes how the findings from Phase I are incorporated into the refinement of graphical rendering for use in the VAI. It then presents the experimental methods and findings for the next three

psychophysically-motivated usability experiments (Exps 4-6) conducted as part of Phase II of this dissertation research.

Chapter 5 elaborates on how the findings from Phase I and Phase II impact the modification of iterative development of the VAI and sets the stage for the final behavioral evaluation. It then details the experimental methods and findings from the behavioral study (exp 7) conducted as part of Phase III of this dissertation research.

Chapter 6 summarizes the findings from the three research phases and provides concluding remarks based on the results from the seven experiments. This chapter also discusses the key contributions of this dissertation, their broader impacts, and provides directions for future research.

2. A REVIEW OF NON-VISUAL ACCESS TO SPATIAL INFORMATION AND ITS CHALLENGES

The aim of this chapter is to lay out the theoretical foundations and practical motivations for using touchscreen-based devices for non-visual graphical accessibility by reviewing literature and existing solutions. The organization of the chapter is as follows: The first section reviews the research related to various existing non-visual graphical access solutions and their pros and cons. The second section provides a brief survey of research related to touchscreen-based graphical access solutions and their limitations. The third section reviews the underlying mechanism of touchscreen-based haptic perception in the context of sensory substitution (visual-to-haptic substitution) and various challenges pertinent to haptic information access and processing. The last section discusses the rationale for development and use of a new interdisciplinary evaluation approach for identifying perceptual parameters pertinent to touchscreen-based haptic interactions.

2.1 A Survey of Non-Visual Graphical Access Solutions

Considerable research has been done in addressing the issue of non-visual graphical accessibility. Some notable work includes: use of raised tactile maps [Golledge 1991; Rowell and Ungar 2003a; Rowell and Ungar 2003b; Rowell and Ungar 2003c], use of force-feedback devices [Hwang and Ryu 2010; Yu and Brewster 2002; McGookin and Brewster 2006], use of verbal descriptions [Giudice and Tietz 2008; Kesavan and Giudice 2012; Taylor and Tversky 1992], use of sonification-based displays [Nees and Walker 2005; Nees and Walker 2008; Walker and Mauney 2010; Walker 2002] and use of multimodal interfaces [Su et al. 2010; Zeng and Weber 2010; Yu and Habel 2012; Xu et al. 2011]. These solutions predominantly rely on exploration of the visual spatial elements via keyboard or mouse interaction, force-feedback devices, or direct physical touch.

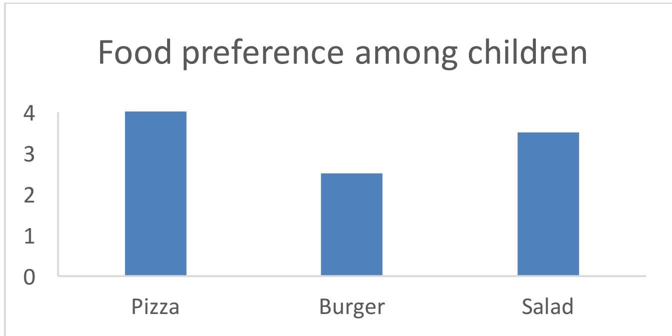

Figure 2.1. Bar graph showing food preference among children

Graphical contents such as maps, graphs, diagrams, etc., are made up of two informational components: (1) spatial and (2) semantic. The spatial component relates to the geometry, topological congruence, and structural aspects of the graphic, while the sematic component relates to the qualitative meaning conveyed by the graphic. For instance, consider a simple bar graph of food preference among children (Figure 2.1). The information such as height, width, and topology of the bars represent the spatial components, whereas the bar names, axis titles, and axis values represent the semantic components. To extract and gain meaningful information from the bar graph, users must have access to both of these information sources. In the sections that follow, I will review various notable non-visual graphical access solutions by categorizing them based on the modality employed. As a thought experiment, think about how each of the following approaches might support *Cody* (our representative persona for BVI people discussed in section 1.1) with access to the example bar graph as you read the following descriptions.

2.1.1 Audio-Based Solutions

Several research efforts have utilized non-speech audio to construct and provide quick overviews of graphical information to blind and visually-impaired (BVI) users. Most of these audio-based solutions were aimed at conveying graphs and statistical data.

Sonification is one of the major techniques used in audio-based solutions. With this approach, visual graph information is mapped onto auditory cues such as pitch, loudness, timbre, or tempo [Brewster

2002; Yu and Brewster 2002; Walker and Mauney 2010]. The AUDIOGRAPH system investigated the use of simple musical sequences or a pattern of musical sequences to convey semantic information [Alty and Rigas 1998]. Following on the AUDIOGRAPH system, audio icons (also called earcons), were used for conveying metaphoric meanings, for example an ascending tri-tone means "up" [Dinger et al. 2008; Encelle et al. 2011]. These approaches showed that sophisticated audio sequences can be used to convey spatial information such as graphs, shapes and path maps. The potential utility of audio as a data-display has led to development of various accessible software packages such as Audio Triangle and the vibro-audio interface developed as part of this dissertation research. While some of the audio-based approaches can be an added value to some well-accepted tactile solutions, the fact that the auditory cues also interfere with environmental sounds significantly limits their utility and ability to perform a task in real-world situations, where auditory attention is generally used elsewhere [Giudice and Legge 2008]. This attention deficit caused by audio could be reduced (or completely avoided) by utilizing audio as a supplementary channel for accessing just the sematic information as opposed to using it as the primary modality for accessing both semantic and spatial information [Klatzky et al. 2014; Soviak 2015; Soviak et al. 2015; Zeng and Weber 2010]. Based on this logic, the vibro-audio interface evaluated in this dissertation utilizes vibrotactile cues as the primary modality for interactions, and supplements it with speech cues for indicating semantic information and audio cues for triggering alerts.

2.1.2 Language-Based Solutions

Accessibility technology such as screen readers use synthesized Text-to-speech (TTS) or pre-recorded human speech as their main form of accessibility for conveying textual information. The most common use of TTS for BVI people is the screen reader (e.g., JAWS by Freedom Scientific or VoiceOver by Apple). In 1975, Ray Kurzweil created the *Kurzweil Reading Machine* and the first OCR technology. Ever since, TTS-based screen readers have become one of the most successful and adopted approaches among BVI users for accessing textual information [Stent et al. 2011]. Several research projects have also explored

the use of speech to convey spatial information such as graphs and images [Ferres et al. 2006; Elzer et al. 2008]. AUDIOGRAF was another earlier approach focused on conveying drawings, where objects around the user's finger in a square would be spoken aloud sequentially [Kennel 1996]. Similarly, Spearcons (highly compressed short sequences of speech) were found to be highly effective in conveying the spoken meaning of graphical objects to the user while not imposing the cognitive load that standard speech incurs on the human listener [Dinger et al. 2008; Walker et al. 2013]. Many non-visual pedestrian navigation systems provide in situ navigation instructions to support navigation [Ishikawa and Kiyomoto 2008; Ishikawa and Montello 2006; Hegarty et al. 2006]. Many studies have also shown that users are able to follow step-by-step navigation using verbal path instructions [Giudice 2004; Helal et al. 2001; Ran et al. 2004; Giudice and Tietz 2008]. These studies demonstrated that language-based displays are efficient in conveying orientation and position information about one's surrounds that are traditionally conveyed through visual access. However, a major limitation of these approaches are that language/verbal descriptions are an interpretive medium that requires cognitive mediation. This makes them less precise, more error prone, and requiring of higher cognitive load than perceptual modalities, such as touch or vision. To better conceptualize this difficulty, the reader is encouraged to visualize a graphical image based on the following textual description, "The figure presents two horizontal lines "*ℓ*" and "*m*" with line "*ℓ*" above line "*m*", and two lines "*s*" and "*t*" that are slanted upward with line "*s*" to the left of line "*t*". Lines "*s*" and "*t*" intersect lines "*ℓ*" and "*m*". The angle above line "*ℓ*" and to the right of line "*t*" is labeled 1, and the angle above line "*m*" and to the left of line "*s*" is labeled 2". Now, compare the mental image to visualizations presented in Figures 3 and 4. The description holds true for both figures but angles 1 and 2 change depending on the reader's interpretation of the words "slanted upwards".

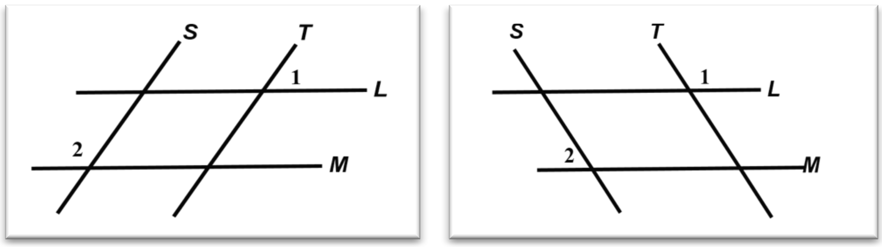

Figure 2.2. (Left) Visualization of the textual description of the figure, (Right) Alternate visualization of the same textual description

Unlike the above verbal description, feeling the same graphical representations through touch does not lead to such ambiguous interpretation, as the spatial information is perceived directly (similar to visual apprehension). This inherent advantage of touch over audio/language motivated the design of the vibro-audio interface evaluated in this dissertation, which utilizes vibrotactile cues for conveying spatial information and speech cues for conveying non-spatial and semantic information.

2.1.3 Force-Feedback Devices

Force-feedback devices have gained considerable attention among assistive technology (AT) researchers because of their ability to physically push and pull a user's body within a fixed or controllable frame of reference. The PHANTOM from Sensable Technologies [Phantom 2015], or the Logitech WingMan force-feedback mouse [Yu and Brewster 2002] represent examples of these force-feedback technologies. In addition to graphical access, efforts with force-feedback devices have been made in various fields such as game interfaces, medical simulators, training simulators, and interactive design software [Kyung and Lee 2009]. Approaches employing force-feedback devices range from simple force-feedback cuing to force-feedback coupled with auditory, vibratory or verbal cues. Some notable work with such devices include; the BATS project for accessing environmental boundaries or feature changes with on-screen graphical information [Parente and Bishop 2003]; a 3-dimensional pen to guide the user's hand in a trajectory, outlining the geometry of simple shapes [Crossan and Brewster 2008]; Virtual Audio Reality [Frauenberger and Noisternig 2003] and Multi-way Visual Analysis [McGookin and Brewster 2006],

which used a force-feedback device coupled with audio cues for presenting graphical information; and the TeDub project (Technical Drawings Understanding for the Blind), which coupled force-feedback devices with verbal descriptions to present node-link diagrams such as UML diagrams [Petrie et al. 2002]. A major advantage of many force-feedback devices is that they can render objects in three dimensions, using both static and dynamic simulations. This means they can provide topographic information for maps such as elevation, orientation, and route information [Magnussen and Rassmus-Grohn 2003]. In addition to being expensive (e.g., the desktop version of PHANToM, which is the cheapest one in the range, is over $10,000 USD), a major disadvantage of these devices is that they are single-point contact displays built on a hardware platform that is non-portable and is generally bulky. Meaning that these devices do not effectively support *edge detection* or *contour following*, which are the basic exploratory strategies employed for tactual information extraction. Furthermore, authoring the stimuli for such specialized devices is expensive and time consuming.

2.1.4 Haptic-Based Solutions

Raised tactile graphics are considered the most frequently used approach for non-visual graphical access [Perkins 2015]. Tactile-based approaches such as tactile pictures or tactile maps have been in use for over 200 years and have the advantage of allowing users to directly feel the graphical information [Eriksson 1998; Golledge 1991]. These approaches usually involve embossing graphical information on non-refreshable media such as paper, thermo-form, plastic sheets, or heat-sensitive swell paper. Unfortunately, none of these approaches support interactive use of graphics or multimodal interactions. This means, once authored, these renderings are static, only include touch-based information, and cannot be updated unless completely reproduced. Also, the information must be authored by specialists in order to be embossed on paper or swell media, which is an expensive and time consuming process.

The advent of computer-based refreshable tactile displays has overcome many of the limitations of paper or swell-based approaches. The most commonly used of all refreshable tactile displays is the

Braille display. These displays are composed of an array of touch stimulation units (also referred to as *taxels or Braille dots*) that dynamically change in time, similar to the screen-based pixels of visual displays [Vidal-Verdú and Hafez 2007]. The haptic stimulation with these refreshable displays is either based on electromagnetic, piezoelectric actuators or electrostatic stimulation [for reviews, see Raja 2011; Palani 2013; O'Modhrain et al. 2015]. When the display is activated, the user traces the area to feel what is on the display. However, the vast majority of these refreshable displays only convey one line of text at a time and do not work for rendering/displaying graphical material. While larger displays suitable for presenting tactile graphics are available, they are extremely expensive (e.g. A4 size displays are around US $50,000). Refreshable tactile displays can be further classified into two categories; static and dynamic. The static-refreshable displays have an array of *taxels* that completely cover the entire width and length of the large flat surface display, such that the entire graphical material is displayed at once. This means the display will be activated only once for a given graphic and subsequently refreshes for different graphics. This is analogous to fixing the display to render a digital image, but once fixed (e.g., the pins are raised), it cannot be changed unless the pins go down and the graphic is erased. Some examples of static-refreshable displays are HyperBraille's BrailleDis 9000 [Völkel et al. 2008], METEC's DMD 12060 [Schweikhardt and Klöper 1984] and NIST [NIST 2002]. In addition to the tactile actuator arrays, the BrailleDis 9000 unit can take multi-touch gestural inputs based on finger gestures over the surface. The major drawback of these static-refreshable displays is their resolution capabilities, which are low even for tactual standards owing to the difficulty of pin spacing. Also, the cell-based structure of Braille (i.e., a 2 x 3 matrix of dots, with each cell separated by at least 2.34mm gaps) means that regular Braille displays are not easily co-opted for the display of tactile graphics.

Unlike static Braille displays, dynamic Braille displays use a small array of *taxels* (finger sized) coupled with a pointer device, such as a mouse, which points over a virtual tactile screen. The tactile pins actuate up and down dynamically based on the position of the mouse on the virtual tactile screen. Examples of

dynamic-refreshable displays include HAPTAC [Hasser 1995], TACTACT [Kammermeier and Schmidt 2002; Kammermeier et al. 2000], and VITAL [Benali-Khoudja et al. 2004]. Although these devices are advanced, efficient, and commercially available, they have not been adopted by the target audience due to their non-portability, single-purpose nature, and their high cost (ranging from $10,000 for the GWP to ~56,000 for the HyperBraille). In addition, rendering graphics on such dynamic displays is a demanding process as it requires significant filtering and simplification of graphical information [Graf 2013; Zeng and Weber 2010]. A few recent approaches have attempted to build low-cost Braille displays by attaching one or two Braille cells to the fingertip or to a mouse and actuating the cells based on the pointer position on a virtual screen [Owen et al. 2009; Rastogi and Pawluk 2013]. The first commercially available pin-array augmented mouse (e.g., VTMouse or VTPlayer) was released by Virtouch Ltd (www.virtouch2.com). Because of their compact design accommodating a single cell of 4 x 8 or two cells of 4 x 4 pin arrays, the resolution of these products are higher than earlier Braille displays and thus can support access to tactile graphics. However, these approaches have also failed to reach the target users as the tactile image is refreshed beneath the fingertip which retains geometric shape cues but does not provide the tangential force cues that a user typically gains by sliding their finger across a line of text during Braille reading. Also, it is difficult to perform *edge detection* and *contour following* using these devices [O'Modhrain et al. 2015], which is one of the key non-visual exploration strategy needed for accessing graphics, as is studied in this dissertation research.

2.2 A Survey on Touchscreen-Based Non-visual Graphical Access Solutions

Touchscreens have become a de facto standard for mobiles, tablets, laptops, smart watches, and many other commercial and house-hold appliances. For instance, over a billion touchscreen units were sold in 2014 alone [Gartner 2017]. Touchscreen-based devices such as smartphones and tablets have opened the door to a new era of multimodal interfaces incorporating combinations of auditory, vibro-tactile, and kinesthetic feedback. As stated in section 1.2, these devices overcome several inherent

shortcomings of the aforementioned traditional non-visual graphical access solutions, such as cost, portability, multi-purpose nature, and inbuilt universal design principles The usage of touchscreen devices among the BVI population has also gone up dramatically from 12% in 2009 to 82% in 2014 [WebAim 2017]. Part of the reason for this surge in touchscreen usage is the intuitiveness of these devices that incorporates non-visual accessibility features such as Apple's VoiceOver for iOS and TalkBack for Android [IOS 2017; Ganov et al. 2009]. Aside from using TTS (as discussed in section 2.1.2) and audio tones for output, both VoiceOver and TalkBack use audio/speech as the main form of input as well [Grussenmeyer 2017]. For instance, Azenkot and Lee found that 90.6% of blind and low vision users have recently used dictation on their smart phones, which was 35% higher than sighted people [Azenkot and Lee 2013]. While these accessibility features support BVI users with textual access and for interfacing with the device, they do not provide access to graphical information such as maps or graphs. To fill this gap, several researchers and developers are utilizing touchscreen devices for supporting BVI users with access to digital graphical materials. In the sections that follow, I will review the most notable touchscreen-based non-visual graphical access approaches by categorizing them based on the visual substitution modality employed.

2.2.1 Touchscreen-Based Haptic-Audio Interfaces

Unlike the traditional audio-based approaches (discussed in section 2.1.1), the translation of spatial information is direct with touchscreen-based auditory interfaces as perception occurs through a combination of touch, audio, and kinesthetic cues. In such approaches, the primary audio cues (sound) are used for indicating contact with the graphical elements and supplementary audio cues (speech) are used to present non-spatial and other semantically-rich information. Examples of audio-based interfaces include *Timbremap*, which uses sonification for indicating indoor layouts using a smartphone [Su et al. 2010], and the *PLUMB* project, which uses sonification to indicate bars on graphs using a tablet [Cohen et al. 2005]. EdgeSonic was another project that attempted to automatically sonify general graphical

information presented in any app or image [Yoshida et al. 2011]. The complementary nature of kinesthetic feedback along with both types of audio cues makes this an intuitive approach, as perception of the stimuli is more direct than speech-based description systems. However, a major drawback of these approaches is that the use of audio as a primary cue can compete and interfere with other environmental sounds. Since access to environmental sounds is critical for BVI people, these audio-based approaches will not be easily adaptable for real-world applications. While conveying semantic information is efficient with audio/speech, conveying spatial information is harder as it leads to ambiguities, as was discussed earlier in section 2.1.2. Considering the perceptual advantage of touch over audio, the vibro-audio interface evaluated in this dissertation utilizes vibrotactile cues for conveying spatial information and audio/speech cues for conveying non-spatial and semantic information.

2.2.2 Touchscreen-Based Surface Haptic Interfaces

Surface haptic interfaces are defined as those that rely on modulating the friction that is created when a fingertip is moved across the flat surface of the touchscreen display [O'Modhrain et al. 2015]. These approaches work by modulating the friction between the fingertip and a surface in a systematic way to indicate contact with on-screen graphical contents. Some approaches have even modulated the amount of force that must be applied by a user to push their fingertip across a rendered feature. There are several techniques currently in development for modulating friction across the finger contact patch, e.g. using electrovibration as in the TeslaTouch [Xu et al. 2011] or by modulating electrostatic force, as is done with the T- Pad [Mullenbach et al. 2014] or by utilizing electro-static screen overlays to generate frictional force, as is done with the Senseg devices (www.senseg.com). These interfaces are still in the research phase and have only been shown to work in limited scenarios (such as indicating buttons in text messaging apps or for supplementing visual cues by haptically indicating edges of on-screen elements). In addition to the drawback of developing and rendering tactile images specifically for such

displays, this approach suffers from a major limitation of forcing users to constantly move their finger for triggering the frictional feedback. If the finger stops moving, the stimulus also stops, meaning that there will not be any feedback to indicate whether they are on or off of the on-screen graphical object. To appreciate this challenge, the reader is invited to imagine a situation where an object would disappear whenever your eyes fixated on it, only to re-appear once you moved your eyes (e.g., made a saccade). This design requirement means that such interfaces are effective as a gaming display where haptic cues supplement visual cues, but at least in their current form, we argue that they are not well suited for presenting non-visual graphical information as a primary interaction style, as is studied in this dissertation research.

2.2.3 Touchscreen-Based Vibrotactile Interfaces

The vibrotactile interfaces discussed here include approaches that employ vibratory feedback for accessing graphical content on touchscreen devices. As stated earlier, most touchscreen interactions are limited to one finger as multi-touch vibration is not possible using current touchscreen devices. To overcome this limitation, several efforts have been made by affixing external vibrators to the fingertips of two or more digits. These efforts have demonstrated that performance with this technique was accurate for exploration of graphs, shapes, charts and maps [Goncu and Marriott 2015; Goncu et al. 2015; Goncu et al. 2010; Petit et al. 2008]. In addition to the added cost of the external hardware, cumbersome setup, and lack of commercial availability, these approaches have various practical limitations as the user cannot perform any other activities with their hands (e.g., picking up a coffee cup) while using this device setup. These shortcomings can be avoided by utilizing vibration motors embedded within the device, but such an approach would force the user to rely on one-finger interactions for graphical access. Despite this limitation, various studies have shown that one finger interactions are efficient in supporting non-visual learning of graphs and shapes [Giudice et al. 2012; Palani 2013; Palani and Giudice 2014; Poppinga et al. 2011; Awada et al. 2013; Tennison and Gorlewicz

2016]. Similarly, educational games such as BraillePlay for BVI children have utilized vibration only feedback to make Braille patterns accessible on touchscreens and have shown promising results [Milne et al. 2014]. With these interfaces, when the finger comes in contact with an on-screen graphical element, the interface triggers vibration to indicate contact. Although the vibration motor(s) causes the entire device to vibrate, the feedback is felt only on the fingertip, as it is the only point of focal contact with the device. This, in turn, creates an illusion that the graphical contents are vibrating. This approach is direct and intuitive as the graphical elements are perceived in an innate manner. Typically, through an embedded vibration motor or a piezoelectric transducer, or with some experimental systems, from an external vibrator attached to the fingertip. With most of these devices, the vibrotactile stimulation is based on an oscillation of frequencies around 250 Hz, which is considered to be most sensitive to vibration detection in the fingertip [Maclean 2008]. Aside from the obvious limitations of any touchscreen-based approaches (i.e., lack of explicit cues for guidance of tactual elements and increased cognitive resources), vibrotactile approaches used in isolation cannot provide non-spatial semantic information, as was discussed earlier in Section 2.1.2. For instance, consider the bar graph example from figure 2.1. Using vibrotactile cues on a touchscreen interface, users can identify the bars, their width/height and the relation between each bar, but they cannot gain sematic information such as axis titles or the name of each bar. To gain such non-spatial semantic information, additional audio/speech cues must be incorporated as is done in the studies discussed in the following section.

2.2.4 Touchscreen-Based Multimodal Interfaces

As stated earlier, a major advantage of touchscreen devices compared to other non-visual interfaces is their ability to provide direct perceptual access to both spatial and non-spatial information via multimodal cues. Each of the aforementioned approaches (in sections 2.2.1-2.2.3) has some modality specific limitations. We postulate that utilizing complimenting multimodal cues will help to overcome such limitations. For instance, the inability of vibrotactile and surface haptic displays to present non-

spatial semantic information can be resolved by implementing speech output. This approach of multimodal cuing significantly reduces the effort in optimizing and down sampling of information to support BVI users in achieving a task of interest. Several projects have demonstrated the advantages of employing touchscreen-based multimodal cues [Warnock, Mcgee-lennon, et al. 2011; Warnock, McGee-Lennon, et al. 2011]. *Touchover* map, is a notable touchscreen-based multimodal approach, which employed vibrotactile and speech cues to access maps on a smartphone [Poppinga et al. 2011]. The *Vibro-Audio interface (VAI)*, evaluated in this dissertation builds on this multimodal approach utilizing vibrotactile, kinesthetic, speech, and audio cues. Earlier evaluations with the VAI have demonstrated that it is an effective approach for accessing and accurately learning various types of graphical information such as shapes, patterns, graphs and path maps [Palani 2013; Giudice et al. 2012]. Promising results from this pioneering work motivated the need for a systematic implementation of a multimodal cuing mechanism that compliments the characteristics and limitations of this new form of information access technology. Building on the findings from this initial work with the VAI, this dissertation research evaluated several key perceptual and cognitive characteristics (and limitations) through a logical progression of eight human experiments. The following section details the theoretical foundations and practical applications that guided the evaluation approach followed in this dissertation.

2.3 Visual-to-Haptic Sensory Substitution

Sensory substitution refers to the use of one spared sensory modality to supply information normally gathered by the impaired sense [Bach-Y-Rita et al. 1969; Loomis et al. 2012; Wall and Brewster 2006]. Some well-known examples of sensory substitution devices (SSDs) include: Braille – substitutes visual text with tactile patterns; vOICe – substitutes visual colors with auditory tones; the tongue display unit (TDU) – substitutes camera-based visual information with electro-tactile signals. Beginning with the pioneering work by Bach-Y-Rita, et, al., several visual substitution aids have been developed to support BVI users [Bach-Y-Rita et al. 1969]. For a review of this concept and the evolution of SSDs over the years,

see [Kay 1974; Petit et al. 2008; Elli et al. 2014; Maidenbaum 2015; Velázquez 2010; Giudice and Legge 2008].

As stated earlier, several non-visual graphical access solutions have been developed over the years but they have frequently failed to reach the intended end-users due to lack of (or improper use of) sensory translation rules. That is, each of the senses (i.e., vision, touch, and audio) are unique in their information encoding and processing characteristics and have different spatial and temporal parameters, field of view, and perceptual saliency. Even with intact vision, accessing and understanding graphical materials (such as the bar graph in Figure 2.1) can be cognitively demanding as it involves three general competencies of increasing complexity: (1) extracting information directly portrayed through the graphical rendering, (2) understanding relationships between individual graphical elements, and (3) drawing inferences [Galesic and Garcia-Retamero 2011]. This cognitively demanding process is even harder to perform with touch due to its sequential processing nature of information extraction, where each element of the graphical material (e.g., each bar, x-axis, and y-axis on the bar graphs from Figure 2.1) must be apprehended individually and consolidated into a holistic 'image' in memory. The success of nonvisual understanding graphical information, such as the bar graph example, will depend on: (1) haptic perceptual constraints in information extraction (i.e., sparse spatial resolution and extrinsic vibrotactile feedback), and (2) constraints pertinent to spatio-temporal integration of extracted information (i.e., integrating sequentially perceived information into a globally coherent mental spatial image). For a non-visual access solution to be truly useful, it is essential that designers recognize these two constraints and go beyond the naïve technique of simply trying to implement a one-to-one haptic analog of the visual graphical rendering on the touchscreen. Towards this end, this dissertation systematically evaluated the perceptual constraints (Chapter 3) and spatio-cognitive constraints (Chapter 4) that are needed in order to develop a set of design guidelines for rendering perceptually-salient and cognitively-valid graphical elements on touchscreen-based haptic interfaces.

2.3.1 Introduction to Haptic Perception

To understand the nuances of touchscreen-based haptic perception, it is necessary to first define what touch means in the context of a sensory modality. In lay terms, the "sense of touch" is commonly referred to as a system that is responsible for all the sensations felt on our skin, such as temperature, texture, pressure, vibrations, pain, and more. However, "sense of touch" implies two functionally distinct components: (1) the cutaneous sense (i.e., stimulation of the skin surface), and (2) the kinesthetic sense (i.e., movements of the limbs and joints). The contribution of these two senses can be delineated into three perceptual categories: (1) tactile perception - mediated solely by variations in cutaneous stimulation, (2) kinesthetic perception - mediated solely by variations in kinesthesis, and (3) haptic perception - where both the cutaneous sense and kinesthesis convey significant information about the perceived object [Jones and Lederman 2006; Loomis and Lederman 1986; Loomis 1981]. Broadly speaking, the term 'Haptics' can be thought of as relating to 'active touch', and most of our everyday life activities involve haptic perception [Lederman 1991; Klatzky and Lederman 2003]. Haptic perception is also found to be served by two distinct subsystems: (1) a 'what' system for recognition, and (2) a 'where' system for localization [Lederman and Klatzky 2009]. This functional distinction can also be observed in the visual and auditory senses. Consequently, almost all of the touchscreen-based graphical access solutions, including the vibro-audio interface studied here, are based on haptic perception as the underlying somatosensory system that can perform recognition and localization tasks, similar to the process when performed by the visual system [Shepard et al. 1971]. To effectively access graphical elements utilizing the haptic modality as a substitute for vision, it is first necessary to understand how the perceived information from haptic cues is encoded, transmitted and processed in memory. The following section provides a broad overview of this process as relates to guiding the investigations on haptic perceptual characteristics (Chapter 3) and spatio-cognitive constraints (Chapter 4) that are pertinent to touchscreen-based haptic information access.

2.3.2 Encoding, Transmitting and Processing Information via Haptic Feedback

Haptic interaction involves the inter-relation of three complex processing components: (1) mechanical stimulation, (2) perceptual processing, and (3) cognitive processing. The information flow begins with skin deformation (via pressure, vibration, etc.) where a range of mechanoreceptors within the skin, encode and transmit the stimulus to the central nervous system (CNS). This sensory input is then integrated and relayed to increasingly higher levels of brain processing for information interpretation [Pasquero 2006; Luk et al. 2006]. The mechanical stimulation of the skin can occur through a variety of interactions, such as tap, stretch, vibrate, indent, compress, and more [Jones and Sarter 2008]. These interactions can be further varied by attributes such as amplitude, frequency, resolution, duration, and signal waveform. Germane to this research, the focus is on vibratory stimulation triggered from the vibration motor embedded within the touchscreen device. In addition to the stimulus encoding and its perceptually-salient attributes, the location of interaction on the body also plays a significant role in the sensitivity / acuity of encoded tactile information. For all the evaluations in this research, the focus will be on the users fingers (their index finger in particular), which is one of the body locations with the highest tactile sensitivity / acuity. Figure 2.2 shows the 2-point touch threshold and point localization threshold as a function of various body locations.

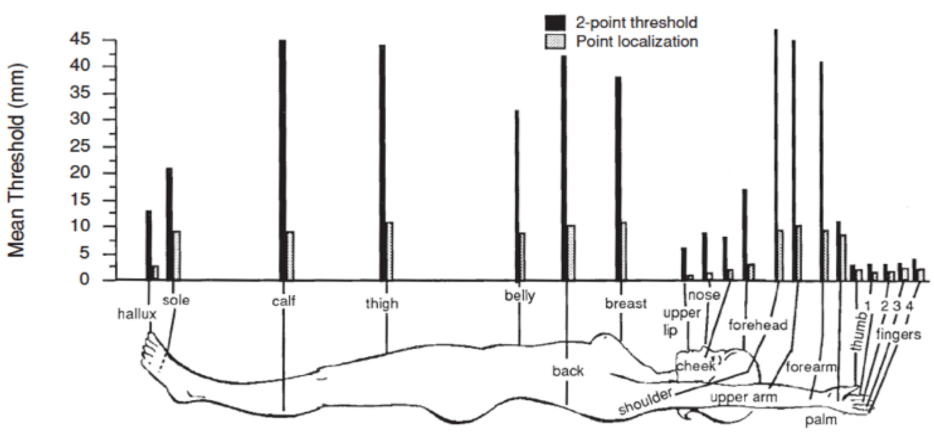

Figure 2.3. Two-point touch and point localization thresholds are shown for various body sites.

**Figure adapted from [Lederman 1991]*

Following mechanical stimulation, the encoding and transmission of the mechanical deformation is carried out by mechanoreceptors embedded in the hairless parts of glabrous skin. These mechanoreceptors are further divided into four types based on their receptive fields and their adaptation rates to the impinging stimulation. The four types of receptors are: *Merkel cells, Meissner corpuscles, Pacinian corpuscles*, and *Ruffini cylinders*. These receptors relate to the primary factors influencing tactile acuity (i.e., the stimulus detection threshold). As shown in Figures 2.3 & 2.4, tactile sensitivity is based on the location of the body being stimulated, as the density of these receptors varies as a function of body location. Higher concentration of receptors (i.e., areas of non-hairy skin) represent smaller spatial thresholds where finer detail can be detected [Kandel et al. 2000].

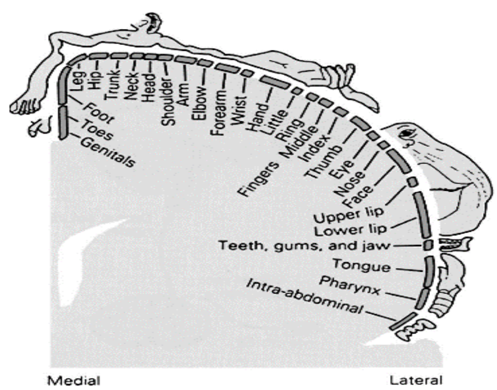

*Figure 2.4. Distribution of tactile sensors in the skin over the entire body. * Figure adapted from [Kandel et al. 2000].*

Over the years, several psychophysical studies have identified the thresholds for innervating these receptors. For a detailed review on these mechanoreceptors, their characteristics, and thresholds, see [Lederman 1991; Loomis 1981]. Of note, some important thresholds include:

(1) Merkel receptors respond to pressure-sensitivity of about 0–10 Hz and are responsible for the detection and identification of spatial patterns such as Braille dots and sharp edges [Johnson and Philips 1981; Van Boven and Johnson 1994];

(2) Meissner corpuscles respond to dynamic skin deformation over a wide and uniform receptive field at 3–50 Hz, and are responsible for detecting low-frequency vibrations. These receptors are also responsible for signaling state changes used for the accurate control of grip forces [Pasquero 2006];

(3) Ruffini cylinders respond to stretching of skin within 0–10 Hz [Maclean 2008]; and

(4) Pacinian corpuscles respond to vibration between 100–500 Hz and are responsible for skin motion (in nanometers) and perception of high-frequency vibration [Maclean 2008]. The "sweet spot" for vibrotactile sensitivity via Pacinian corpuscles is considered to be 250 Hz, which is the frequency utilized for the vibro-audio interface evaluated in this dissertation.

These psychophysically-derived parameters form the basis for designing or rendering tangible graphical stimuli (e.g., tactile maps, Braille) as haptic perception with tangible graphics is facilitated primarily by mechanical stimulation of skin receptors. By contrast, haptic perception of touchscreen-based graphical stimuli is not solely based on mechanical stimulation. Indeed, contact with the screen will result in mechanical stimulation of the receptors that only encode properties of a flat featureless glass surface, except for vibratory stimulation that changes depending on whether the fingertip is on or off the rendered graphical stimuli. To perceive the stimulus information, the signal from the vibratory stimulation (innervating the Pacinian corpuscles) must be integrated with *kinesthesis* (i.e., proprioceptive cues) of the contact finger while also ignoring the mechanical stimulation of the other three receptors. This identified information must then be associated with an on-screen graphical element to derive meaningful inference. This means, detection (or discrimination) of an on-screen stimuli via vibro-audio interface is not only dependent on mechanical stimulation, but is also dependent on proprioceptive cues and the users' ability to associate the sensory information to an on-screen graphical element. Considering these distinctions, the on-screen graphical elements should be rendered at a size that is perceptually-salient for detection and discrimination via vibro-audio interface. Towards this end, this dissertation research empirically identified three key perceptual parameters to guide

visual-to-haptic conversion and rendering of graphical lines for touchscreen-based vibrotactile access. Identification of these key perceptual parameters based on a core graphical component is expected to serve as the building blocks for future research using touchscreen-based information access solutions.

2.4 Empirical Identification of Haptic Perceptual Parameters

Currently, almost all touchscreen applications utilize a size of ~0.27-0.55inch (i.e., the average finger digit size) as a standard target size for user input interactions. The logic is that if the target size is equal or greater than the size of an average finger digit, then the probability of contact and accurate gesture execution is increased. Some current industrial standards include: 0.27 inch for iPhones, 0.35 inch for Windows Phone UI design, 0.4 inch for Nokia, 0.4 to 0.55 inch for Ubuntu UI design, and MIT Touch Lab suggests 0.4 to 0.55 inch [Wroblewski 2010]. While such standard target sizes work well for haptic interactions aided with visual cuing (i.e., where touch is primarily utilized as an input channel), they cannot be adopted for non-visual haptic interactions that must mediate both input and output operations, as is evaluated in this dissertation research. Similarly, the few studies that have evaluated the usability of touchscreen-based interfaces as a non-visual graphical access solution have all utilized different parameters for their evaluations. For instance, a target size of ~0.17inch was used in the *Timbremap* project for map exploration using an iPhone [Su et al. 2010]. A rendering width of ~0.35inch (which is 8 times the size of traditional embossed graphics) was utilized as the optimal line width for rendering and accessing shapes, graphs and maps using a Vibro-Audio Interface (VAI), similar to the system studied here, on a 7.0inch android galaxy tablet [Raja 2011; Palani 2013]. A rendering width of ~0.20 inch was used for shape identification in the GraVVITAS project, which used a Dell Latitude XT Tablet as the rendering platform [Goncu and Marriott 2015]. Similarly, Tennison et al., compared a width of ~0.15inch to ~0.31inch in a shape identification task and found that users were able to identify smaller shapes with a thin border (0.15inch) at rates comparable to those with 0.31inch borders, after first being exposed to the larger shapes [Tennison and Gorlewicz 2016]. Such unguided use of random

parameters has limited the scope and usability of these promising approaches. On the one hand, rendering graphical elements at the aforementioned sizes consumed unnecessary screen space and by extension led to increased effort in information extraction. On the other hand, rendering them at a sub-threshold size will not support users with accurate perception of on-screen information and by extension will lead to failure of the approach being advanced. For any non-visual graphical access solutions to succeed, it is of utmost importance that the original visual graphical material is schematized and rendered based on parameters that are empirically identified to ensure haptic perceptual saliency. To achieve this goal, a systematic approach is needed for identifying touchscreen-based haptic perceptual parameters.

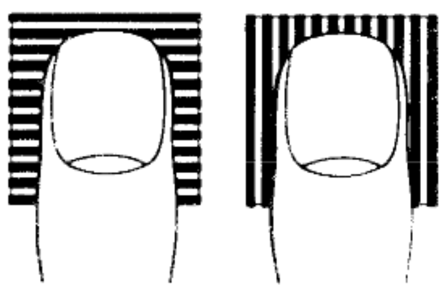

*Figure 2.5. Evaluation of tactile grating orientation via static finger position. *Figure adapted from (www.neurobiography.info/)*

For empirical identification of tactile perceptual parameters (i.e., haptic spatial resolution), researchers typically employ two techniques: (1) the two-point threshold, and (2) a grating threshold. Two-point threshold is defined as the smallest separation at which two points applied simultaneously to the skin can be clearly distinguished from a single touch point [Johnson and Philips 1981]. By contrast, the grating threshold is the smallest separation of ridges at which grating orientation (of a grooved stimuli) can be clearly distinguished from a single touch point [Craig 1993]. Numerous psychophysical studies have utilized these two approaches in identifying key perceptual parameters that must be considered for schematizing and developing tangible graphics (i.e., physical stimuli) to facilitate accurate tactual perception and exploration. Some notable parameters for tangible graphics that rely on pressure-based

tactile stimulation include: an average threshold of 2.8mm for two-point discrimination [Loomis 1981]; a threshold of 0.17mm for detecting direction of a moving point [Craig 1999]; 0.87-0.94mm for gap detection [Loomis and Lederman 1986]; a gap width of 1.7mm for judging orientation [Van Boven and Johnson 1994; Johnson and Philips 1981]; and a frequency range of 100–500 Hz (with an optimal value of 250Hz) for vibration response via *Pacinian* corpuscles (see [Loomis 1981; Robles-de-la-torre 2006] for detailed reviews). While these parameters support designing/rendering of tangible graphics that are perceived through pressure-based cutaneous stimulation, they cannot ensure saliency when adopted for rendering digital graphical elements on touchscreen interfaces. In addition, the aforementioned thresholds are all based on mechanical stimulation via static finger movements, but as discussed earlier, detection (or discrimination) of on-screen stimuli via the vibro-audio interface is a multi-factor phenomenon that is not only dependent on mechanical stimulation, but is also dependent on proprioceptive cues (i.e., active finger movements) and the users' ability to associate the sensory information to an on-screen graphical element. There is a dearth of knowledge in the literature specifying the perceptual characteristics of touchscreen-based haptic information access. To fill this gap, this research developed a new evaluation approach aimed at identifying the perceptual parameters for touchscreen-based haptic interactions. The following section details this new approach.

2.4.1 A New Approach for Evaluating Perceptual Parameters Pertinent to Touchscreen-Based Non-Visual Haptic Interactions

Identification of the absolute threshold for stimulus detection or the just-noticeable difference for discrimination via traditional psychophysical procedures typically involves plotting of psychometric functions, which represent the mathematical relationship between an attribute of a stimulus (e.g., length, width, or height) and the perceptual values assigned to these stimuli. Utilizing such traditional procedures will not be meaningful for touchscreen-based haptic interactions because of two key challenges. First, the perception of an attribute (width/length) of on-screen graphical elements via

touchscreen-based haptic cuing is not merely based on cutaneous sensation, as the users' finger digit is only feeling a flat featureless glass screen. The user response is based on an indirect feedback mechanism (e.g., vibration) that indicates whether the finger is 'on' or 'off' the stimuli. Second, the underlying device operates based on a pixel coordinate system that narrows the finger contact area down to a single on-screen pixel (i.e., centroid of the finger's contact area). The extrinsic feedback (i.e., triggering of a vibration cue) occurs based on whether or not this centroid pixel overlaps with the pixels of the on-screen rendered graphical element. Perceiving stimulus details via this chance-based feedback mechanism demands active finger movements and proprioception. For instance, consider detecting the width of a tactile grating as shown in figure 2.5 versus detecting the width of an on-screen rendered graphical line via vibrotactile feedback on a touchscreen device. With the static finger contact on the tangible grating, users can predict the width of each grating and the number of gratings. By contrast, the same static finger contact on a touchscreen only allows users to predict whether the centroid of the contacted finger digit overlaps with the on-screen graphical material. They cannot perceive any meaningful information such as the width of the line. While traditional psychophysical procedures can be used to identify the detection threshold based on such static finger position (i.e., the chance of correctly hitting an on-screen graphical element), the identified parameter will not be meaningful for use in practical scenarios (e.g., perceiving stimulus width/length). Accordingly, an active exploration method was employed for the current evaluations. While employing an active exploration-based psychophysical procedure will address the foundational and technological aspects of the VAI, the method will not address the usability aspects of touchscreen-based non-visual information access. It is postulated here that simply identifying a perceptual threshold based on traditional psychophysical procedures will not be sufficient for addressing the overarching goal (i.e., development of a viable touchscreen-based non-visual graphical access solution) of this dissertation. As stated in section 1.2, most of the extant solutions have failed in addressing non-visual graphical access because of the

disconnect between foundational research (i.e., haptic perception), technological research (touchscreen interfaces), and usability research. For the vibro-audio interface advanced in this dissertation to not face the same negative consequences of previous projects, it is necessary that the evaluations are made with an interdisciplinary approach connecting the three research domains. Building on this interdisciplinary approach, a new testing paradigm was developed for use in this dissertation research, called a psychophysically-motivated usability evaluation. This approach was used to evaluate touchscreen-based haptic perceptual parameters by coupling aspects of traditional psychophysical procedures based on active stimuli exploration with aspects of standard usability evaluation paradigms (i.e., how accurately a human user can use a newly designed interface to access, learn, and use the presented information). The motivation for this new testing paradigm is two-fold: (1) the empirically-validated stimulus measurements at the end of each experiment should reflect a particular characteristic of haptic (vibrotactile) perception that is valid based on standard psychophysical methods employing rigorous statistics and repeated trials, and (2) the evaluation method should also determine that the measured parameter is not just perceptually-valid but is also functional for usage in practical scenarios, while also revealing the impact (positive/negative) of its implementation on the overall usability of the interface being evaluated. Utilizing this new testing paradigm, chapter 3 investigated three key perceptual parameters to support detection and discrimination of graphical lines on the vibro-audio interface.

3. IDENTIFICATION OF TOUCHSCREEN-BASED HAPTIC PERCEPTUAL PARAMETERS

This chapter covers Phase I of the dissertation research and is aimed at studying key touchscreen-based haptic perceptual characteristics. Three psychophysically-motivated usability studies (Exps 1-3) were conducted that established three key perceptual guidelines for rendering haptically perceivable graphical lines on touchscreen-based interfaces. Experiment 1 evaluated the minimum line width that best supports detection of on-screen rendered graphical lines via vibrotactile feedback. Experiment 2 examined the minimum interline gap width that best supports discrimination of two or more vibrotactile lines that are rendered parallel to each other. Experiment 3 investigated the minimum interline gap width that best supports discrimination of two or more oriented vibrotactile lines that are emanating from a vertex. Findings from the three studies contributed novel concepts pertinent to touchscreen-based haptic perception and filled an important gap in the literature on vibrotactile touch perception characterizing best practices for the design and implementation of nonvisual graphical stimuli rendered on touchscreen devices. The design guidelines established from the three experiments set the basis for future research on touchscreen-based information access technology and also motivated the methodological and design choices adopted in the next four dissertation experiments.

3.1 Measuring Haptic Perceptual Parameters through a Psychophysically-Motivated Usability Study

As discussed in chapter 2, this dissertation developed a new testing paradigm called a psychophysically-motivated usability evaluation that combines the traditional psychophysical procedure (i.e., a method of constant stimuli) with a standard usability evaluation paradigm (i.e., how accurately a human user can use a newly designed interface to access and learn information). In accordance with the psychophysical paradigm, the evaluation (exps 1-6) followed a response-based forced-choice procedure involving active exploration of a pre-defined set of stimulus magnitude (i.e., different line widths). In accordance with the usability paradigm, the evaluations focused on usability of the vibrotactile feedback mechanism to

indicate graphical lines and support extraction via a touchscreen-based non-visual interface. As such, the primary focus on each of the following experiments was to measure the detection and discrimination thresholds for rendering graphical lines that will support accurate perception via vibrotactile feedback on touchscreen devices. It should be noted that the terms 'detection' and 'discrimination' can have different meanings in different contexts and are also used interchangeably in the literature. To clarify the meaning of these terms in the current evaluations, they are defined as follows based on [Gescheider 1997; Prins 2016],

Detection is used as a process of identifying the presence or absence of an on-screen rendered experimental stimulus (e.g., threshold for rendering line width).

Discrimination is used as an experimental task for measuring interline-gap detection (e.g., distinguishing two or more on-screen rendered experimental stimuli from each other).

3.1.1 Scope of the Evaluation and Design of the Vibro-Audio Interface

As stated in section 1.2.2, the scope of this dissertation research is narrowed to focus only on rectilinear line (and polyline) features of graphical materials. Accordingly, all other geometries (e.g., point and region) and any non-spatial semantic information (e.g., map legends, landmark names, axis titles, etc.) will not be studied in the context of non-visual haptic perception. However, region-based graphical elements and supporting semantic information will not be excluded completely as they must be comprehended for performing practical tasks as part of the usability testing paradigm (e.g., to compare the relative height of bars on a bar graph using bar labels or wayfinding between landmarks on a map using landmark names). For the current evaluations using the vibro-audio interface, graphical lines (which is the primary measure for evaluation) will be conveyed only through vibrotactile cues, and all other region-based elements and semantic information will be conveyed through vibrotactile cues supplemented with audio and/or speech output such that users can apprehend the overall graphical information.

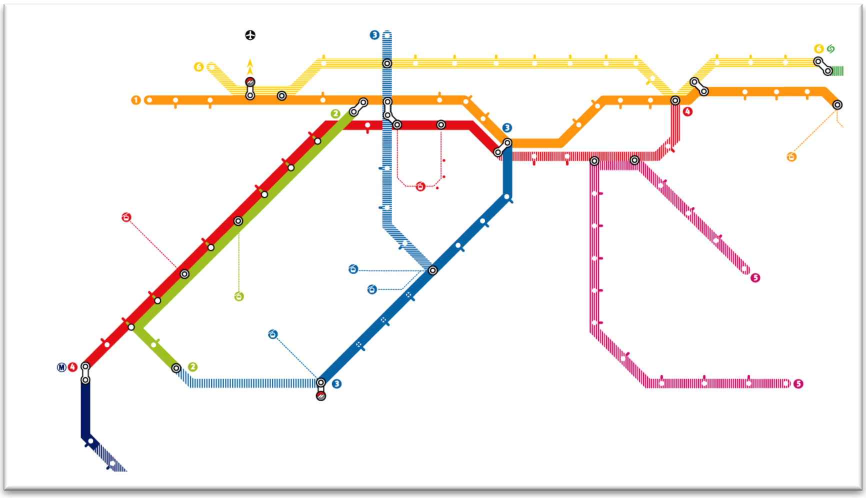

Figure 3.1. Sample transit map

As stated earlier, lines are a foundational element and a crucial spatial construct for rendering graphical materials such as graphs and maps. Often graphical materials will be comprised of multiple line (polyline) segments that are rendered adjacent to each other, or overlapping and intersecting each other (e.g., see the blue and yellow paths on the transit map in Figure 3.1). Similarly, the line features could also be rendered at cardinal, ordinal, or at oblique angles. Detecting and discriminating these different forms of line features is the basic and preparatory step needed towards ultimate apprehension of the overall graphical information. Towards this end, three psychophysically-motivated usability experiments were designed as part of the Phase I research to investigate and identify the minimum line width for detecting on-screen vibrotactile lines (Exp 1), the minimum interline gap width for discriminating vibrotactile lines rendered parallel to each other (Exp 2) and the minimum interline gap width for discriminating oriented vibrotactile lines (Exp 3). The sample size for each experiment was determined using the G*Power calculator via a priori power analysis (based on an alpha of 0.05, an expected power of 0.95, and an effect size of 0.25 as suggested by [Faul et al. 2007; Cohen 1988]). All three experiments were approved by the Institutional Review Board (IRB) of the University of Maine and

written informed consent was obtained from all participants. In the sections that follow, I will elaborate on the design, method, and results of the experiments.

3.2 Experiment 1: Vibrotactile Line Detection

As stated earlier, the ability to detect graphical lines (e.g., each path on the transit map) using vibrotactile feedback is the preparatory step towards apprehension of global graphical content via non-visual access on touchscreen-based interfaces. For instance, consider a sample scenario of Cody trying to access information on the subway map (Figure 3.1) without the use of vision. Detecting individual subway paths (i.e., lines) represents the first step towards accessing and gaining global information about the subway map. Furthermore, starting the evaluation with lines is a good design choice as parameters identified for this core graphical element can be easily extended to other graphical elements that form the global structure of most graphical material. To support comprehension of graphical information, each vibrotactile line must be rendered at a minimum width that not only supports its detection but should also preserve the spatial structure and topology of the original visual graphical rendering. To this end, Experiment 1 was designed to identify the minimum line width for rendering haptically perceivable graphical lines. As stated earlier, the experiment was designed as a response-based forced-choice procedure with a pre-defined stimulus set (i.e., psychophysical procedure) and the task was to mimic a practical scenario of counting the number of bars on a bar graph by tracing across the graph using the prototype vibro-audio interface (i.e., usability testing paradigm).

3.2.1 Method

Participants: Fifteen blindfolded-sighted participants (7 females and 8 males, ages 19-32) and twenty blind and visually-impaired (BVI) participants (9 males and 11 females, ages 21-74, BVI demographic details are presented in Appendix - Table 1.) were recruited for this experiment.

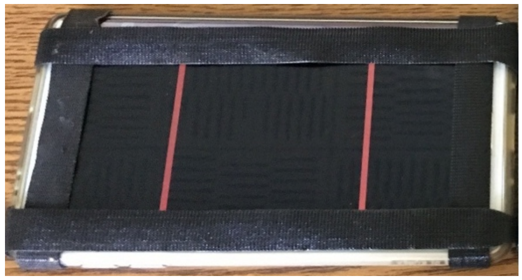

Figure 3.2. Randomly generated lines rendered on the galaxy note4 edge phablet.

3.2.2 Stimuli and Apparatus

The stimulus set consisted of seven different line widths (0.125, 0.25, 0.5, 1, 2, 4, and 8mm). These line widths were chosen because the smallest width of 0.125mm was approximately equivalent to the size of a single pixel on most current touchscreen displays. From this base, the stimuli was increased linearly by a factor of 2 up to 8mm, which is known from previous studies to be equivalent to the size of the contact patch of the index finger, which is the most commonly used finger with touchscreen-based interactions [Palani et al. 2016; Palani and Giudice 2017]. The stimuli were presented using the prototype vibro-audio interface (VAI) implemented on a 5.6inch Galaxy Note4 Edge Android phablet. Whenever an onscreen rendered graphical line was touched by the user, the device's vibration motor was triggered, creating the perception of focal vibrotactile stimulation on the user's finger. The device comes with two feather touch buttons that do not provide any tactile feedback. Hence to avoid potential errors or interruption during experimental trials, the buttons were cover with Velcro straps (see Figure 3.2). In addition, the device comes with an edge screen that acts as a standalone secondary touchscreen. This side screen was used by the experimenter as the controlling area for quickly manipulating experimental trials without distracting the participant from their experimental tasks.

3.2.3 Procedure

The study followed a within-subject design with each participant performing 84 line counting trials (resulting in 360 observations for each tested line width). A trial rendered 1, 2, or 3 lines on the screen, with all lines being of the same width per trial. The lines were randomly generated and were evenly

spaced for the two and three line trials. In each trial, participants were asked to move their finger across the screen from left to right at a constant speed and to verbally indicate the number of vibrotactile lines perceived during this scan upon its completion. Once they indicated the number, the experimenter quickly changed the stimuli using the side screen and the change was indicated to the participant via speech message stating “Next”. They then brought their finger back to the left side of the screen and started tracing again. 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 and for the 2 participant groups (sighted vs. BVI).

3.2.4 Results and Discussion

The accuracy in line detection was compared using a mixed model (7x2) ANOVA across the seven tested widths as a within-subjects factor and the two participant groups (sighted versus BVI) as an independent factor. Results revealed a main effect of line width ($F(6, 2382) = 451.94$, $p < 0.001$, $\eta^2 = 0.053$), but no reliable differences between the two participant groups ($F(1, 397) = 4.605$, $p > 0.05$, $\eta^2 = 0.014$) or the interaction between the line widths and the participant groups ($F(6, 2382) = 2.153$, $p > 0.05$, $\eta^2 = 0.011$).

Line Width (in mm)	**Sighted**		**Blind**	
	Mean (%)	**SD**	**Mean (%)**	**SD**
0.125	21	40.9	26	44.2
0.25	35	47.8	47	50
0.5	75	43.4	76	42.9
1	97	18	98	15
2	100	0	100	0
4	100	0	100	0
8	100	0	100	0

Table 3.1. Mean line detection accuracy across tested line widths and participant groups

Post-hoc paired sample t-tests based on Bonferroni correction indicated that the detection accuracy with the line widths 0.125, 0.25 and 0.5mm were significantly different from each other and exhibited significantly lower detection accuracy than the remaining four line widths (see Table 3.1 for means and

SDs and Table 3.2 for *p* values). However, there were no statistical differences observed between detection of line widths 1, 2, 4, and 8mm (see Table 3.2 for *p* values).

Line Width (mm)	**0.125**	**0.25**	**0.5**	**1**	**2**	**4**	**8**
0.125	NA	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.00	NA	0.00	0.00	0.00	0.00	0.00
0.5	0.00	0.00	NA	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	NA	1.00	1.00	1.00
2	0.00	0.00	0.00	1.00	NA	1.00	1.00
4	0.00	0.00	0.00	1.00	1.00	NA	1.00
8	0.00	0.00	0.00	1.00	1.00	1.00	NA

Table 3.2. p-values for paired sample t-tests comparing the seven line-widths

These results indicate that rendering graphical lines at a width of 1mm is sufficient for tasks requiring simple line detection via vibrotactile cuing. While designers tend to go with the motto “bigger is better”, results here demonstrate otherwise. While rendering lines at widths 0.5mm can provide ~75% accuracy and maximize screen space, it comes at the cost of losing detection accuracy, which is neither acceptable for use in real-world applications nor a wise design decision. As stated earlier in section 3.1, the rationale for adopting the psychophysically-motivated usability evaluation paradigm is to not only achieve perceptual saliency as would be identified via traditional psychophysical procedures (i.e., at least ~75% accuracy), but is to identify a parameter that is also functional for usage in practical scenarios and when implemented enhances the overall usability of the interface. Based on this logic, a 1mm line width (which led to a 97% detection accuracy) is suggested here as the minimum line width that best supports detection of vibrotactile lines. While adopting a line width wider than 1mm may improve saliency and ensure 100% accurate detection, doing so will consume more screen space than necessary, which is argued here as a poor design decision given the conjunction of the low information bandwidth of vibrotactile perception and the limited availability of screen real estate on most touchscreens. To effectively utilize screen space and maximize detection performance, designers should carefully consider the tradeoff between employing vibrotactile line widths above and below the 1mm width, as empirically determined here. However, depending on the criticality of the task that could demand 100% detection

accuracy, the line width can be increased to higher values (i.e., 2mm or more) at the cost of losing screen space. It should be noted that the suggested guideline of using a 1mm line width pertains only to detection of graphical lines using vibratory cues and not for more complex perceptual tasks, such as line tracing and contour following, which are evaluated in Phase II of this dissertation (see Chapter 4).

3.3 Experiment 2: Discriminating Vibrotactile Lines

As stated earlier, graphical materials often have multiple lines rendered in close proximity to each other. For instance, consider the sample scenario of Cody trying to access the subway map in Figure 3.1, where there are multiple transit lines that construct the actual map. To be recognized as a distinct transit line, each of the individual lines must be separated from its neighboring adjacent line by an interline gap wider than the minimum perceivable gap width. If the transit lines of this example were to be rendered in their original form for non-visual access on the touchscreen display, Cody will not be able to discriminate them via haptic cues owing to the sparse spatial resolution of touch. On the other hand, rendering them using too large of an inter-line gap is a poor design decision, as it will consume unnecessary display space on the limited screen real-estate available on touchscreen devices. In addition to the actual interline-gap, the width of the bounding vibrotactile lines could also influence the perception of the gap between them. This is because the vibrotactile feedback on touchscreen devices is generated via actuation of an embedded vibratory motor, which operates in a binary mode (i.e., on and off). For all commercial touchscreen-based devices (irrespective of the computational capability), there will be some mechanical lag in turning the motor on or off that in turn can cause a lag in the perceived vibrotactile feedback. This lag in turning the motor off, could in principle, create a spurious perception of a line being wider than its actual size. This spurious haptic perception could mask the gap and result in two lines being incorrectly perceived as one (see Figure 3.3). For accurate discrimination of vibrotactile lines, the inter-line gap must be greater than the minimum width that avoids such spurious haptic perception. Accordingly, the second experiment was designed to identify the minimum interline-

gap width that supports discrimination of two or more vibrotactile lines (rendered parallel to each other) while also evaluating whether the bounding line width causes spurious haptic perception due to the lag in vibrotactile feedback imposed by the device.

Figure 3.3. Randomly generated lines rendered on the galaxy note4 edge phablet.

3.3.1 Method

Participants: Eighteen blindfolded-sighted participants (9 females and 9 males, ages 19-33) and eighteen blind and visually-impaired (BVI) participants (7 males and 11 females, ages 20-74, BVI demographic details are presented in Appendix A-Table A.2.) were recruited for this experiment.

3.3.2 Stimuli and Apparatus

The stimulus set consisted of five gap widths (i.e., 0.25, 0.5, 1, 2, and 4mm). 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 the spurious haptic perception 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).

3.3.3 Procedure

The study followed a within subject design with each participant performing 54 line counting trials (resulting in 162 observations for each tested gap width for each participant group). A gap trial rendered 1, 2, or 3 pairs of lines with each pair separated by a set gap width. The line widths and gap widths were held constant within each trial. In each trial, 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 the number to the experimenter upon completing the trial. To confirm that participant responses were based on gap detection (and not guesses), 9 dummy trials (i.e., trials where the rendered stimuli did not have interline gaps) were added to the 45 gap detection trials, resulting in 54 line counting trials. Each participant took between 20 and 30 minutes to perform the 54 trials. Based on this design, the accuracy in gap detection was compared for both blindfolded-sighted and BVI participant groups as a function of: (1) five gap widths (i.e., space between a pair of parallel vibrotactile lines), and (2) three line widths.

3.3.4 Results and Discussion

Gap Width (in mm)	**Sighted**		**Blind**	
	Mean (%)	**SD**	**Mean (%)**	**SD**
0.25	37	48.4	43	49.7
0.5	55	49.9	63	48.4
1	68	46.8	73	44.6
2	78	41.7	79	40.8
4	91	28.2	91	30.7

Table 3.3. Mean gap detection accuracy for the two participant groups as a function of gap widths

Gap Width (in mm)	**0.25**	**0.5**	**1**	**2**	**4**
0.25	NA	0.000	0.000	0.000	0.000
0.5	0.00	NA	0.009	0.000	0.000
1	0.000	0.000	NA	0.192	0.000
2	0.000	0.000	0.192	NA	0.005
4	0.000	0.000	1.000	0.005	NA

Table 3.4. p-values for paired sample t-tests comparing the five gap-widths

Line Width (in mm)	**Sighted**		**Blind**	
	Mean (%)	**SD**	**Mean (%)**	**SD**
1	49	50.1	53	50
2	65	47.8	69	46.4
4	84	37	87	34.1

Table 3.5. Mean gap detection accuracy for the two participant groups as a function of tested line widths

The accuracy in gap detection was compared using a mixed model (5x2) ANOVA across the five tested gap widths as a within-subjects factor and the two participant groups (sighted versus BVI) as an

independent factor. Results revealed a main effect of gap width ($F(4, 1288) = 138.3$, $p < 0.001$, $\eta^2 = 0.30$), but no reliable differences between participant groups ($F(1, 322) = 0.920$, $p > 0.05$, $\eta^2 = 0.475$) or the interaction between the gap widths and the participant groups ($F(4, 1288) = 1.482$, $p > 0.05$, $\eta^2 = 0.079$). Subsequent post-hoc paired sample t-tests based on Bonferroni correction indicated that the gap widths 0.25 and 0.5mm were significantly different in detection accuracy from each other and exhibited significantly lower detection accuracy than the remaining three gap widths (see table 3.4). Similarly, the accuracy in gap detection was compared using a mixed model (3x2) ANOVA across the three tested line widths as a within-subjects factor and the two participant groups (sighted versus BVI) as an independent factor. Results revealed a main effect of line width ($F(2, 1076) = 172.648$, $p < 0.001$, $\eta^2 = 0.243$), but no reliable differences between the participant groups ($F(1, 538) = 1.339$, $p > 0.05$, $\eta^2 = 0.325$) or the interaction between the line widths and the participant groups ($F(4, 1288) = 0.060$, $p > 0.05$, $\eta^2 = 0.769$). Subsequent post-hoc paired sample t-tests based on Bonferroni correction indicated that accuracy with the three line widths increased linearly with an increase in line width and were significantly different from each other. Of the tested gap widths, only the 2mm and 4mm gap widths exhibited an overall detection accuracy greater than is required by traditional psychophysical procedures (i.e., 75% detection accuracy). However, further analysis including the line widths revealed that the two gap widths (i.e., 2mm and 4mm) exhibited greater than 90% detection accuracy when coupled with a 4mm line width as opposed to 87% with 2mm bounding lines and 74% with 1mm bounding lines. These findings suggest that the ability to accurately discriminate parallel vibrotactile lines is not only dependent on the width of the interline gap but is also dependent on the actual width of the bounding vibrotactile lines. These results demonstrate that the line and gap width parameters should not be treated separately when creating / authoring vibrotactile graphical information. As stated earlier, the aim for these studies is to achieve as close to 100% detection accuracy such that it supports practical usage in common scenarios. Based on this intent, a 4mm interline gap width bounded by vibrotactile lines of width 4mm (which led

to ~96% detection accuracy) is suggested here as the minimum line width and gap width that best supports detection of and discrimination of parallel vibrotactile lines. As stated earlier in exp1, designers must decide the rendering parameters based on the criticality of the task at hand. If the task demands highly accurate gap detection at a lower line width, then the gap width can be increased to higher values (i.e., greater than 4mm) at the cost of losing screen space. It should be noted that this suggested guideline pertains only to detection and discrimination of parallel vibrotactile graphical lines and not for oriented lines that subtend an angle between them, which is evaluated in the following experiment.

3.4 Experiment 3: Discriminating Oriented Vibrotactile Lines

As was discussed 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 (i.e. feel it as vibrating) but they cannot directly perceive any other meaningful stimulus information, such as its width/length/angle without active finger movements. To extract meaningful information using a one finger interaction, as is required for use on 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 [Loomis and Lederman 1986; Lederman and Klatzky 1987]. While experiments 1 and 2 established the minimum line and gap widths for detection and discrimination 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 red and blue transit lines in Figure 3.1.). For identifying such oriented lines and judging the angle subtended between them, BVI users such as Cody will typically employ a 'circling' strategy (see figure 3.3 left), where they move their finger in a circular pattern around the intersection as their exploratory procedure [Raja 2011; Palani and Giudice 2014; Palani and Giudice 2017]. Based on this exploration strategy, the arc of the circle (see figure 3.3 left) formed during the act of executing the circling EP is the interline gap for oriented vibrotactile lines. From a geometric

standpoint, the straight-line distance (see figure 3.3 right) between two oriented lines is the cord length (cord length = 2r sin (θ/2)). It is postulated here that this cord length (and by extension the angular separation, i.e., the arc length) should be wider than the minimum perceivable gap width for supporting accurate discrimination of adjacent oriented vibrotactile lines emanating from an intersection/vertex.

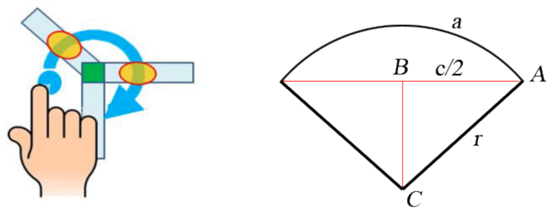

Figure 3.4. (left) Intersection circling strategy: Adapted from [Raja 2011], (right) Geometric representation of cord length 'c'and radius 'r'

The cord length is 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 cannot be fixed at a constant value as it varies depending on the angle (θ) subtended between oriented vibrotactile lines and the radius (r) of the circle formed by the user while performing the 'circling' exploratory procedure. For instance, at a circle radius of 1-inch and a 4mm cord length, the user can (in theory) discriminate oriented lines separated by an angular magnitude of 5°, but by increasing their radius to 2-inches, they should be able to discriminate oriented lines separated by an angular magnitude as low as 2°. Acknowledging the dependency between these three variables, experiment 3 was designed to identify the minimum cord length that supports detection and discrimination of oriented vibrotactile lines.

3.4.1 Method

Participants: Eighteen blindfolded-sighted participants (9 females and 9 males, ages 19-34) and eight BVI participants (3 males and 5 females, ages 25-74, BVI demographic details are presented in Appendix A-Table A.3.) were recruited for this experiment.

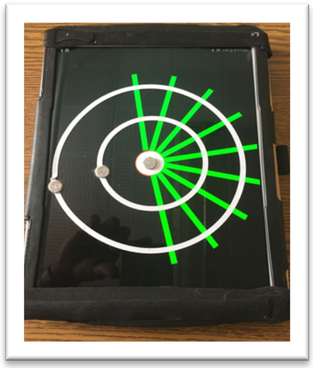

Figure 3.5. Experimental device with circular stickers for two radiuses and tactile markers denoting the start points

3.4.2 Stimuli and Apparatus

The stimulus set was designed as a simple line layout where multiple lines were converging to/diverging from an intersection point at the center (Figure.3.4). The number of lines in each stimulus set ranged from 5 to 9 based on Miller's "The Magical Number Seven, Plus or Minus Two" [Miller 1956]. To evaluate the influence of radius in supporting discrimination of oriented lines, two conditions were designed and evaluated. 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 vertex/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 was translated to a ~5° angular magnitude. To evaluate the influence of cord length (i.e., actual gap) on the discrimination 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 (meaning the radius of the two primary conditions increased and decreased by a factor of 2). Similar to experiments 1 and 2, the stimuli were presented using the vibro-audio interface (VAI) implemented on a touchscreen equipped tablet computer - 10.1 inch Galaxy Tab 3. 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 Figure 3.5). 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).

3.4.3 Procedure

The study followed a within-subjects design. A trial rendered 5, 6, 7, 8, or 9 lines on the screen (for example see Figure 3.4). 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 within the script. In each trial, participants were asked to start at the reference start point (indicated by a tactile marker) and to count the number of lines perceived in a full 360° circuit by tracing along the circular path (either at a 1-inch or 2-inch radius depending on the condition). Upon returning to the start point, they lifted their finger from the display and verbally indicated the number of lines perceived during the 360° scan. Each participant performed 28 line counting trials in each circling condition (resulting in 180 observations for each tested angular magnitude). Each participant took between 20 and 40 minutes to complete the entire experiment.

Angles (in degrees)	**1-inch circling condition**				**2-inch circling condition**			
	2	5	9	22	2	5	9	22
2	NA	0.005	0.000	0.000	NA	0.000	0.000	0.000
5	0.005	NA	0.011	0.000	0.000	NA	0.667	1.000
9	0.000	0.011	NA	0.956	0.000	0.667	NA	1.000
22	0.000	0.000	0.956	NA	0.000	1.000	1.000	NA

Table 3.5. p-values for paired sample t-tests comparing the four tested angles and two circling conditions

3.4.4 Results and Discussion

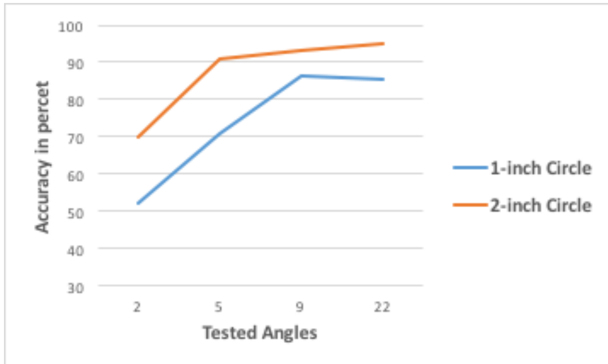

Figure 3.6. Oriented line detection accuracy as a function of four tested angles and two circling conditions for the sighted group (left) and the BVI group (right)

Accuracy in oriented line detection was compared using a mixed model (4x2) ANOVA across the four tested cord lengths as a within-subjects factor and the two participant groups (sighted versus BVI) as an independent factor. Results revealed a main effect of cord length ($F(3, 774) = 28.810$, $p < 0.001$, $\eta^2 = 0.10$), but no reliable differences between the participant groups ($F(1, 258) = 0.230$, $p > 0.05$, $\eta^2 = 0.18$) or the interaction between the cord lengths and the participant groups ($F(3, 774) = 1.66$, $p > 0.05$, $\eta^2 = 0.006$). Subsequent post-hoc paired sample t-tests based on Bonferroni correction indicated that for both circling conditions accuracy in line detection for trials with cord lengths 4mm and below were significantly lower when compared with cord lengths greater than 4mm (see table 3.5). But there was no significant differences in line detection accuracy for the trials with cord lengths greater than 4mm (i.e., 9°, and 22° for 1-inch and 5°, 9°, and 22° for 2-inch). This finding indicates that a 4mm cord length is sufficient to accurately detect and discriminate oriented vibrotactile lines when using a '*circling'* strategy. This parameter is in line with the results found in exp-2, which established a 4mm gap width for accurate detection of parallel vibrotactile lines. It should be noted that the finding is pertinent only to the current context of using a '*circling'* strategy for identifying oriented lines emanating from an intersection. While it is argued here that this is the best strategy to use, the results are not necessarily generalizable to other/all tactual learning/tracing strategies.

3.5 Summary

The motivation for Phase 1 of this dissertation research (described in this chapter) was to establish the building blocks for rendering non-visual graphical information on touchscreen-based devices using vibrotactile stimuli. Three psychophysically-motivated usability experiments were conducted that identified three core perceptual parameters for rendering vibrotactile lines, namely:

(1) Based on the findings from experiment 1, it is suggested here that the vibrotactile lines should be rendered at a width of at least 1mm for supporting tasks that require simple detection of vibrotactile lines on touchscreen-based non-visual interfaces,

(2) Based on the findings from experiment 2, it is suggested here that a line width of at least 4mm in conjunction with an inter-line gap of at least 4mm should be maintained for accurate detection and discrimination of distinct vibrotactile lines rendered parallel to each other on touchscreen displays.

(3) Based on the findings from experiment 3, it is suggested here that a cord length of at least 4mm should be maintained for accurate detection and discrimination of oriented vibrotactile lines when using a 'circling' exploratory strategy for identifying lines emanating from an intersection/vertex.

4. EVALUATION OF SPATIO-COGNITIVE CHARACTERISTICS PERTINENT TO COMPREHENSION OF VIBROTACTILE LINES

This chapter covers Phase II of the dissertation research and is aimed at evaluating two key spatio-cognitive characteristics pertinent to touchscreen-based non-visual haptic interactions: (1) spatio-temporal integration, and (2) development of a global spatial image. The two characteristics were assessed through three psychophysically-motivated usability studies (Exps 4, 5, & 6). Experiment 4 evaluated users' ability to trace vibrotactile lines and judge their orientation. Experiment 5 extended the evaluation of exp-4 by investigating users' ability to trace, conceptualize, and build accurate mental spatial images of multi-leg spatial path patterns. Experiment 6 evaluated whether vibration could be presented as a warning cue (as opposed to a guiding cue) for supporting tactual learning on touchscreen-based haptic interfaces. Based on the results from these three studies, in conjunction with the Phase I outcomes, a set of design guidelines were developed for rendering vibrotactile lines on touchscreen interfaces.

4.1 Building Mental Representations Of Graphical Information Via Non-visual Haptic Perception on Touchscreen Devices

As stated in section 2.1, graphical content is comprised of two information components: (1) spatial information and (2) semantic information. Consider, for example, a simple corridor map of a shopping mall as shown in Figure 4.1. There are four stores (landmarks) and three corridors. Each of the three corridors are diverging from one vertex/intersection (i.e., Dick's sporting goods) and also each of the corridors are oriented at different angles.

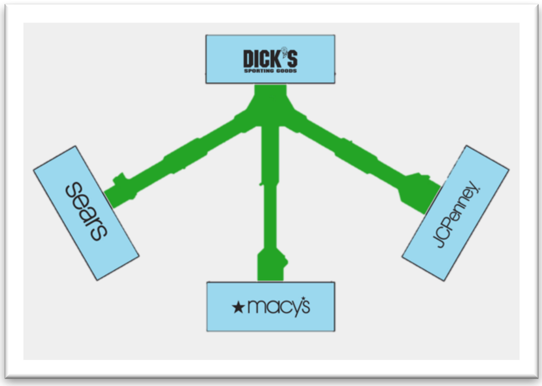

Figure 4.1. Indoor corridor layout of a Shopping Mall.

To build meaningful mental representations of this shopping mall layout, users must cognitively combine both the spatial and semantic information into a consolidated global representation (i.e., an accurate cognitive map). To be truly useful, any non-visual graphical access solution should provide meaningful access to both of these information components. As detailed in section 3.1.1, the focus of evaluation in this dissertation research is on rectilinear lines and polyline geometries and accordingly, the vibro-audio interface was designed to convey these line-based information sources through purely haptic (vibro-tactile) feedback. All other components (i.e., spatial, non-spatial and semantic) were conveyed via a combination of vibrotactile, audio, and speech output. For instance, while learning the shopping mall layout (as in Figure 4.1) using the prototype VAI, the corridors (i.e., line-based geometries) were conveyed only through vibrotactile feedback, the stores (i.e., regions) were conveyed through vibrotactile feedback supplemented with an audio (monotone) cue, and the store/landmark names (i.e., non-spatial semantic components) were conveyed through speech output. It should be noted that evaluating the characteristics of this separation of modality for specifying different information components is not the focus of this research. As exemplified in section 2.2.1, touch leads to the most direct perception of spatial information (that is most similar to visual apprehension) and that this perceptual advantage was the motivation for utilizing vibrotactile feedback as the primary feedback mode for the vibro-audio interface. Accordingly, for the evaluations within the scope of this dissertation,

the interface parameters (i.e., vibration for line-based spatial information and a combination of modalities for other information components) were kept constant with the goal of assessing users' ability to detect, discriminate, trace, and build an accurate mental spatial image of the presented graphical information.

During visual learning of graphical information, vision aids in performing two important activities in a synchronous manner: (1) identifying spatial structure, and (2) relating the identified contents based on their position, structure, and orientation subtended with respect to the visual axis [Galesic and Garcia-Retamero 2011]. Of the two activities, one aids in visual perception (i.e., detection and discrimination of the spatial elements) and the other aids in simultaneous integration of multiple spatial elements into a globally coherent mental spatial image of the presented graphical information. By contrast, with touch, these two activities must be performed by two separate sensory subsystems in a serial, sequential manner (i.e., one activity after the other). For instance, while learning graphical information from touch via a touchscreen-based non-visual interface (such as the VAI) using just one finger, the mechanoreceptors of the contact finger are used to identify the graphical elements via vibrotactile cues, and the kinesthetic sensory system (i.e., movement and orientation of the fingers, arms and joints) relates the different parts of one or more graphical elements [Klatzky et al. 2014].

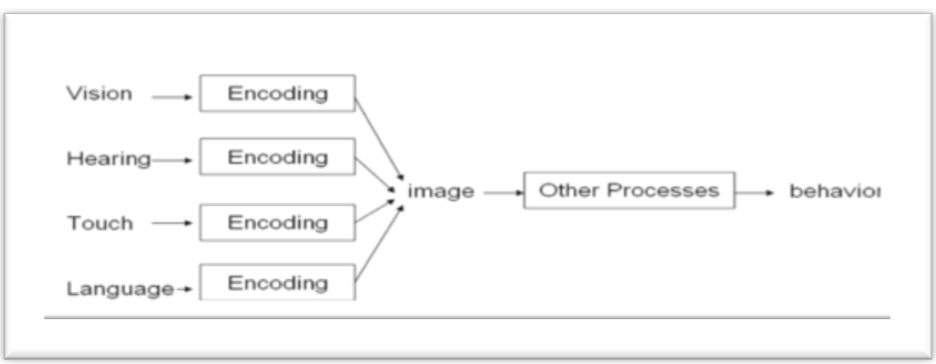

*Figure 4.2. Functional equivalence of mental spatial representations and subsequent behavior derived from different modalities. *Figure adapted from [Giudice et al. 2013]*

Despite differences in the underlying learning process (i.e., parallel versus sequential), many studies have shown that representations from different modalities (i.e., vision, touch, and audio) can all lead to the development of spatial images in working memory (see Figure 4.2), which support subsequent spatial behaviors in a functionally equivalent manner [Avraamides et al. 2004; Giudice et al. 2011]. It is this functional equivalence that forms the basis for an effective sensory substitution aid. As stated in section 1.3, the design of the vibro-audio interface (VAI) evaluated in this thesis, is not proposed as a solution to mimic visual graphical representations for haptic access. Instead, the design is motivated to support development of accurate mental representations and subsequent spatial behaviors based on the presented graphical information in a functionally similar manner to that of learning with visual access. Several studies have suggested that haptic input (using traditional hardcopy tangible graphics) can lead to spatial representations in memory that are functionally equivalent to those obtained from visual input [Cattaneo et al. 2008; Giudice et al. 2011; Giudice et al. 2009]. However, learning touchscreen-based haptic renderings using the VAI means that, in addition to the inherent challenges of haptic perception and tactual learning via the three-step information extraction process, users must also overcome two other challenges: (1) perform exploratory procedures (*EP*) using just one finger to identify graphical elements, and (2) synchronously relate the spatial information (via haptic feedback) and the semantic information (via auditory feedback) in order to build a meaningful mental representation of the presented graphical information. Owing to these challenges, it is unclear whether this new form of information access technology will support development of accurate mental representations of the perceived graphical information as was found with the haptic/visual equivalence of the previous studies. Towards this end, Phase II of this dissertation investigated whether users can build a globally coherent spatial image of graphical information perceived via vibrotactile feedback on touchscreen interfaces.

4.1.1 Measuring Spatio-Cognitive Characteristics through a Psychophysically-Motivated Usability Evaluation

Phase I of this dissertation research identified three core perceptual parameters for accurate detection and discrimination of vibrotactile lines. However, for comprehending the global spatial information, user should perform a '*line tracing*' behavior in addition to detection and discrimination of individual line segments. The term '*line tracing*' is commonly referred to in the literature as '*contour following*', which is a type of exploratory procedure utilized for identifying object properties during haptic exploration [Klatzky et al. 2014; Lederman and Klatzky 2009]. For traditional tangible graphics, *contour following* means tracing an edge *(i.e., line)* on a raised-line drawing or tactile map using cutaneous perception on the finger digit. However, such cutaneous perception is not applicable for touchscreen-based haptic interactions. Thus, in the context of the current evaluations, the term '*line tracing*' is defined as the exploratory procedure that is used for following an on-screen rendered vibrotactile line segment, either by the user placing their finger on the line and moving in a particular direction (figure 4.3 left) or by moving their finger back and forth across the line and moving in a particular direction (figure 4.3 right). Building on the findings from Phase I, three new psychophysically-motivated usability experiments were conducted as part of the Phase II research to investigate and identify the that support accurate *line tracing* behavior.

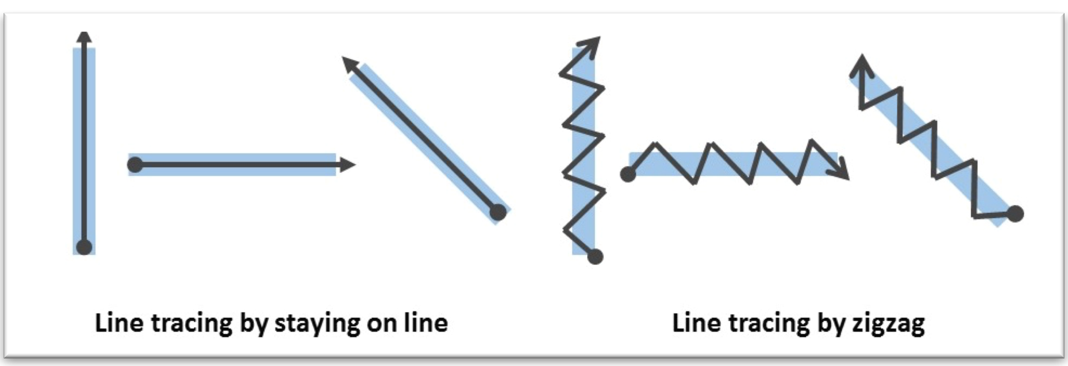

Figure 4.3. Illustration of line tracing exploration strategy

Earlier evaluation with the VAI [Palani and Giudice 2014; Palani 2013; Palani and Giudice 2017], found that the ability to non-visually access, learn, and mentally represent graphical material via vibrotactile feedback is similar between blindfolded-sighted and BVI users. This finding is congruent with Experiments 1-3 of this dissertation, which also found no differences between blindfolded-sighted and BVI groups, suggesting that the ability to perform perceptual tasks is similar between the two groups, irrespective of visual status. Given the similarity in performance between these two groups, it is argued here that blindfolded-sighted participants serve as a reasonable sample for the Phase II evaluations. Although these evaluations are primarily made with blindfolded-sighted participants, the identified guidelines are relevant to both participant groups. Thus, to add support for our belief in the efficacy of this system for providing graphical access to BVI individuals, formative evaluations were also conducted with BVI participants in these studies. Accordingly, for each of the three experiments the sample size for blindfolded-sighted participants was determined using the G*Power calculator via a priori power analysis (based on an alpha of 0.05, an expected power of 0.95, and an effect size of 0.25 as suggested by [Faul et al. 2007; Cohen 1988]). The formative BVI evaluations were done with a focus on assessing usability of the VAI approach in supporting non-visual graphical access. As such, four participants took part in experiment 4, and eight participants each in experiments 5 and 6. The number of BVI participants for each of the experiments were based on: (1) their availability to participate in experiments conducted at the campus, and (2) the ability to conduct the experiment in off-campus locations. Experiments 5 and 6 were based on a smaller phablet device and its testing task relied only on embossed paper stimuli. In other words, the design made it easier to transport the experimental set-up to other locations and thus resulted in twice the sample size as with experiment 4. Irrespective of these logistical details, the sample sizes used in these experiments are in line with traditional usability studies aimed at assessing preliminary efficacy of assistive technology [Sears and Hanson 2012; Shneiderman et al. 2009]. All three experiments were approved by the Institutional Review Board (IRB) of the University of Maine and

written informed consent was obtained from all participants. The following sections elaborate on the design, method, and results of these three experiments.

4.2 Experiment 4: Vibrotactile Line Tracing and Orientation Judgments

For guarantying accurate and efficient spatial behavior (such as navigating within a shopping mall), it is crucial for the user to quickly and accurately trace the vibrotactile lines (i.e., corridors) and correctly judge their orientation. The ability to judge individual line-orientation has been extensively described in the psychophysical literature with both vision and touch [Appelle 1972; Baud-Bovy and Gentaz 2012]. This research has shown that perceptual variation occurs based on tangible line stimulus orientation and that participants are more accurate when predicting vertical or horizontal orientations over obliquely oriented stimuli. Although formal research has not been conducted on orientation judgments based on active exploration of vibrotactile lines, user feedback and informal observations from earlier studies has revealed that people exhibit difficulty in tracing lines and detecting their orientation when they deviate from horizontal and vertical orientations [Gershon et al. 2016; Palani and Giudice 2014; Giudice et al. 2012]. Accordingly, experiment 4 was designed to assess users' ability to judge the orientation of individual vibrotactile lines rendered on touchscreen devices using one finger exploration. The study was also designed to simultaneously measure the minimum line width that best supports line tracing behavior facilitated via touchscreen-based vibrotactile cuing. Similar to previous experiments, this experiment was also designed as a response-based forced-choice procedure with a pre-defined stimulus set (i.e., following standard psychophysical procedures) and the task was to mimic a practical scenario of judging line-orientation using the vibro-audio interface (i.e., usability testing).

4.2.1 Method

Participants. Eighteen blindfolded-sighted participants (9 females and 9 males, ages 18-33) were recruited for this experiment. In addition, four blind and visually-impaired (BVI) participants (3 males

and 1 female, ages 28-43, BVI demographic details are presented in Appendix A-Table A.4.) were also recruited for this study to do formative assessment of the trend identified from the sighted group.

4.2.2 Stimuli and Apparatus

The stimulus set consisted of 36 different line-orientations represented as linear path segments of an indoor corridor map (e.g., a corridor segment connecting Sears and Dick's on the shopping mall in Figure 4.1). Each path was rendered at a unique orientation representing a stimulus set of 36 orientations (i.e., 0° to 350° at 10° intervals). Findings from exp1 suggested a 1mm line width for detection of vibrotactile lines. Since *line tracing* and orientation judgements require more complex behaviors than simple detection, it was unclear whether the detectable line width of 1mm would be sufficient for this task. Hence, to determine the minimum line width that best supports accurate *line tracing* behavior and line-orientation judgements, the 36 line orientations were tested across 3 line widths (i.e., 1, 2, and 4mm). The 36 line orientations and 3 line widths were balanced across 108 orientation judgment trials. All the line stimuli were presented using the vibro-audio interface (VAI) implemented on a touchscreen equipped tablet computer - 10.1 inch Galaxy Tab 3. The lines rendered were given a constant vibration - an infinite repeating loop at 250Hz with 100 percent power. The start and end of each line was indicated via additional speech output indicating "Entrance" and "Exit" respectively. The user's finger movement behavior was tracked and logged within the touchscreen device and used for measuring learning time.

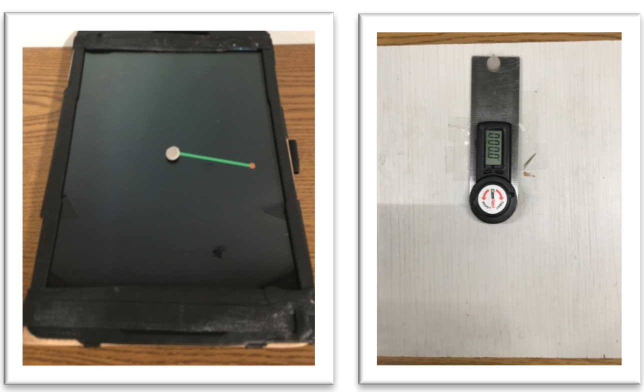

Figure 4.4. Randomly generated oriented lines rendered on the experimental device and (right) the digital pointing device used for reproducing orientation

4.2.3 Procedure

The study followed a within-subject design with each participant performing 108 line tracing and line-orientation judgment trials. In each trial, participants started at the entrance of a simulated hallway at the center of the screen, which was indicated via an audio message and a tangible (2mm) marker affixed to the screen. They then scanned the screen to: (1) identify the vibrotactile line and (2) trace the line until they reached its endpoint, indicated by an auditory message saying "exit". The device was then removed. Participants were then asked to reconstruct the line-orientation from memory by physically adjusting a digital pointing device (figure 4.4 right). Participants performed 2 practice trials and 3 learning-criterion trials before performing the 108 experimental trials (resulting in 792 observations for each tested line width and 66 observations for each tested orientation). During the practice session, the experimenter gave corrective feedback as necessary to ensure that participants fully understood the task. Participants then performed 3 learning-criterion trials where they had to trace an onscreen line segment and successfully reproduce the orientation of the perceived lines (i.e., within +/- 10 degrees of error for the rendered line orientation) before moving onto performing the experimental trials. Each participant took between 40 and 60 minutes. Based on this design, line tracing times and accuracy in reproduced line orientations were compared between the 36 orientations and 3 line widths.

4.2.4 Results and Discussion

A repeated measures ANOVA revealed that the tracing time differed significantly based on the width of the rendered vibrotactile lines ($F(2, 1941) = 25.598$, $p < 0.001$), but not on the orientation of the line ($F(35, 1908) = 1.145$, $p > 0.05$). Post-hoc paired sample t-tests with Bonferroni correction revealed that the tracing time was significantly different ($p < .001$) between the three tested line widths, with 4mm being the fastest and 1mm being the slowest.

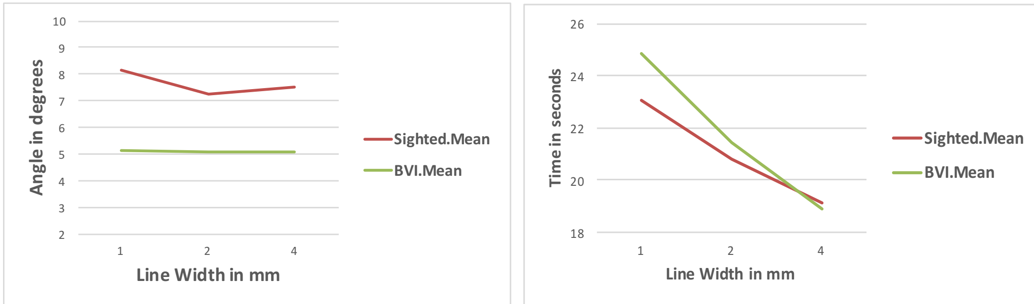

Figure 4.5. Mean angular error (left) and Mean tracing time (right) as a function of line width and participant groups.

Similarly, an ANOVA revealed that reproduction accuracy significantly differed between the 36 line orientations ($F(35, 1908) = 2.566$, $p < 0.001$), but no reliable differences between the 3 line widths ($F(2, 105) = 0.805$, $p > 0.05$). The mean angular error across the 36 line-orientations (figure 4.5) suggests that users were able to accurately judge vibrotactile line-orientation (as low as ~7°). Post-hoc paired sample t-tests with Bonferroni correction revealed that the reproduction accuracy was significantly different ($p < .001$) between the three tested line widths, with 4mm lines being the most accurate.

Since BVI participants were employed here to do formative assessment of the trend from the sighted group, the data from the BVI group was only analyzed descriptively. Comparing the mean tracing times and angle reproduction accuracy between the two groups (figure 4.5), data suggests that the BVI group exhibited faster line tracing behavior and more accurate reproduction of line-orientation. This superior performance was expected for BVI participants as they are familiar with this mode of learning and have prior experience using one finger for learning graphical information. Overall, results from the two groups and tested line widths, it is suggested here that rendering vibrotactile lines at a width of 4mm best supports line tracing behavior and judgement of different line orientations. It should be noted that the superior performance with the 4mm width is based on only single straight-line segments. As such, this finding cannot be generalized to graphical materials comprised of more than one line segments. Accordingly, experiment 5 extended the findings from this experiment to complex spatial path patterns comprised of multiple line segments.

4.3 Experiment 5: Building Mental Representations from Spatial Path Patterns

Consider the sample scenario where our representative persona *Cody* needs to explore a subway map using the vibro-audio interface and gain knowledge to plan his route. To successfully apprehend the global spatial structure of the subway map (i.e., paths, stations, junctions, etc.,), *Cody* should be able to access and trace multiple line segments (i.e., transit lines) and understand the connectivity between these segments in order to build a globally coherent spatial image. Towards this end, experiment 5 was designed with a two-prong focus: (1) to evaluate users' ability to build a mental representation of multi-leg spatial path patterns, and (2) to empirically measure the minimum line width that best supports line tracing and integration of individual line segments into a globally coherent spatial image of the spatial paths. Similar to the previous experiments, this experiment was also designed as a response-based forced-choice procedure with a pre-defined stimulus set. A pattern matching task was utilized to assess the accuracy of the developed mental representation.

4.3.1 Method

Participants. Eighteen blindfolded-sighted participants (8 females and 10 males, ages 18-33) were recruited for this experiment. In addition, eight blind and visually-impaired (BVI) participants (3 males and 5 females, ages 24-74, BVI demographic details are presented in Appendix A-Table A.5.) were also recruited for this study as part of a formative assessment.

4.3.2 Stimuli and Apparatus

The stimulus set consisted of four different spatial path patterns. Each pattern consisted of a start point, three legs (line segments) that were connected by two junctions (vertices), and an end point. The four path patterns were balanced for complexity in terms of length of each line segments, number of vertices, and leg orientation. For instance, path1 did not have any right-angled (90°) vertices, path2 only had right-angled (90°) vertices, path3 had one right-angled (90°) and one acute-angled (45°) vertex, and path4 had one right-angled (90°) and one obtuse-angled (135°) vertex.

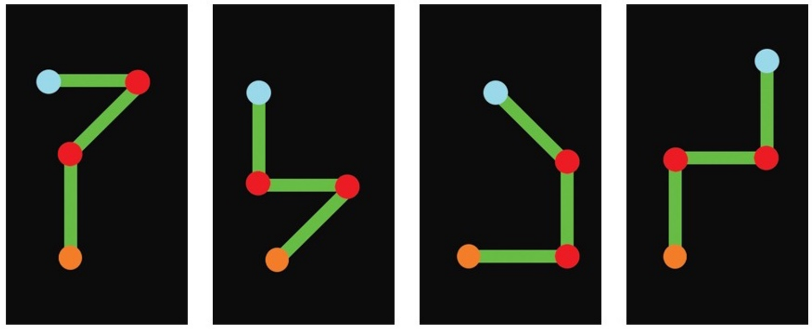

Figure 4.6. Experimental stimuli: four different path patterns

For purely haptic feedback to be useful in such situations, the lines rendered on touchscreens should maintain a width that not only supports accurate extraction or angular judgement but also should aid in the development of an accurate mental representation of the perceived spatial pattern. The three earlier experiments (1, 2, and 4) that compared different line widths have all shown a linear trend of increased performance with a corresponding increase in line width. While the widths established in each of the experiments holds true for the particular task tested in those experiments, the earlier results on vibrotactile line width cannot be generalized to the more complex spatial learning task evaluated in this study. Hence, to understand the influence of line width on learning spatial path patterns and the subsequent development of mental representations, the four path patterns were tested across six different line widths (1, 2, 3, 4, 5, and 6mm). The line widths for this set used a base width of 1mm – as was found from experiment 1 – and increased linearly up to 6mm. The 6 line widths and 4 path patterns (see Figure 4.6) were balanced across 24 path matching trials. All 24 path patterns were rendered using the vibro-audio interface implemented on the same 5.6inch Galaxy Note4 Edge Android phablet. In each trial, the path segments were indicated using vibratory feedback based on the UHL effect "Engine1_100" which uses a repeating loop at 250 Hz with 100% power. The start point, end point, and vertices were all indicated using a pulsing vibration based on the UHL effect "Weapon_1," which uses a wide-band 0.01 s pulse with a 50% duty cycle and a 0.02 sec period. In addition to vibrotactile feedback, the start point, the end point, and two vertices were also indicated via speech output that stated, “Start”, “End” and

“Junction” respectively. The user’s finger movement behavior was tracked and logged within the device and used for measuring learning time and analyzing tracing strategy.

4.3.3 Procedure

The study followed a within-subjects design where each participant performed 24 path learning trials (resulting in 108 observations for each pattern and 72 observations for each tested line width). In each trial, participants were asked to trace the spatial path once from the start point to the end point. Upon reaching the end, the device was removed. Participants were then asked to perform a spatial pattern matching task where they had to identify the just learned spatial path pattern from three geometrically similar alternatives embossed on hardcopy paper. Based on this design, the time taken to trace the entire path pattern, the time spent on individual line segments, the time spent on vertices and the accuracy in pattern matching was compared as a function of 4 patterns and 6 line widths and across two participant groups (sighted and BVI).

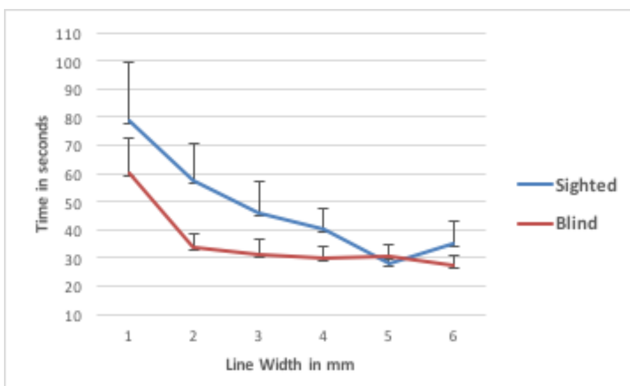

Figure 4.7. Mean tracing time as a function of line widths and participant groups

4.3.4 Results and Discussion

Tracing time here is interpreted as an indicator of spatio-cognitive effort required for perceiving and conceptualizing the spatial path pattern. That is, the greater the tracing time, the higher the cognitive effort. A repeated measures ANOVA revealed that the tracing time differed significantly based on the width of the rendered vibrotactile lines ($F(5, 426) = 6.352$, $p < 0.001$). Post-hoc t-tests, based on

Bonferroni correction, revealed that path tracing time was significantly worse with 1mm and 2mm line widths as compared to the other 4 line widths (see Figure 4.7). But the difference was not statistically significant between the 3, 4, 5 and 6mm line widths, indicating that a line width of 3mm and above is effective for performing line tracing with vibrotactile cues.

Line Width (in mm)	**Sighted**		**BVI**	
	Mean (in seconds)	**SD**	**Mean (in seconds)**	**SD**
1	74.26	97.391	60.19	43.592
2	54.49	73.791	34	14.185
3	42.49	46.73	30.97	19.12
4	38.67	35.888	29.75	14.986
5	26.72	11.385	30.31	16.464
6	32.94	38.638	27.16	14.926

Table 4.1. Mean tracing time and standard deviation as a function of two participant groups

Similarly, the tracing time was significantly different between the four paths patterns tested, independent of line width ($F(3, 428) = 4.41$, $p < 0.005$), with path4 (i.e., the path with one right-angled and one obtuse-angled vertex) yielding the lowest tracing time. Subsequent post-hoc *t*-Tests between the time spent on vertices, based on Bonferroni correction, showed that participants spent significantly ($p<0.05$) more time at vertices comprised of acute-angles (M = 29.59sec) compared to those with obtuse-angles (M = 20.17sec) or right-angles (M = 10.59sec). This result is in line with the difference in tracing time between spatial path patterns, which showed that participants took the most time to trace paths with acute-angled vertices (i.e., path 1 and 3). Paired sample comparisons between the line tracing time for individual line segments, revealed that the tracing time for horizontal lines was significantly faster than for oriented lines ($t(251) = -2.146$, $p <0.033$). While this was expected and is congruent with prior studies using traditional tangible media [Appelle 1972; Baud-Bovy and Gentaz 2012], the tracing time for vertical lines did not reliably differ from oriented lines or the horizontal lines (all *p*s>0.05). These differences in tracing times for the three (i.e., horizontal, vertical and slanted) lines could be attributed to the ergonomics of hand and finger positions. That is, participants had to

bend/twist both their wrist and finger for tracing oriented paths. By contrast, tracing vertical or horizontal paths was ergonomically easier as they only have to stretch/fold the finger (for vertical) or twist the wrist (for horizontal) tracing. For the pattern matching task, a discrete scoring was applied based on the correctness of matching (i.e., 1 if correct, 0 otherwise). Findings from the ANOVA and post-hoc paired sample t-tests revealed that the line width did not statistically impact performance on matching accuracy (all ps>0.05). The matching accuracy for all tested line widths was above 95%, indicating that participants were able to develop an accurate mental representation of the perceived path patterns for all tested line widths.

The trend in the data from the sighted group was also observed for the BVI group (see table 4.1). By comparing the mean tracing times between the two groups (figure 4.7), it is evident that the BVI group exhibited faster line tracing behavior. This trend is similar to experiment 4 and the superior performance of BVI participants is attributed to their familiarity with this mode of learning and prior experience using one finger for learning graphical information. Overall, the tracing times for the entire path pattern and the tracing for individual line segments here, in conjunction with findings from experiment 4, suggest that rendering vibrotactile lines at a width of 4mm would best support users with employing exploratory procedures (Eps), tracing and apprehending on-screen rendered spatial path patterns via vibrotactile feedback on touchscreen interfaces.

4.4 Experiment 6: Building Mental Representations of Spatial Path Patterns using Vibration as a Warning cue

Previous studies have shown that a constant vibration on the fingertip can lead to sensory fatigue, limiting a user's ability to perceive vibratory cues over time [Craig 1993; Raja 2011]. Indeed, a few participants in experiment 5 and in earlier studies with the VAI [Palani 2013; Giudice et al. 2012] have also self-reported that they felt numbness in the fingertip after tracing for a prolong period (after ~45-60 minutes). Experiment 6 was designed to investigate the possibility of reversing the feedback mechanism

of the interface by utilizing vibrotactile feedback as a negative-warning cue as opposed to a positive-guiding cue. This means, rather than following the path by tracing the vibrotactile cue representing the path itself, as was used in experiment 5, participants here must try to trace the path, indicated by an ‘off’ signal between the two vibrotactile lines. The experiment design was adopted from previous work by Loomis and colleagues which compared an Off-course and On-course vibrotactile cue mode for guiding users when walking a route using a handheld Haptic Pointer Interface, with results showing that off-course vibrotactile feedback is sufficient for supporting route guidance behavior [Marston et al. 2007; Klatzky et al. 2006]. For instance, imagine the subway map scenario, where *Cody* has to learn the transit lines by feeling the borders of the path as opposed to feeling the path itself, as implemented in exps 4 & 5. A similar example would be to follow a corridor path with a negative ‘off’ signal and feeling the two borders/walls along the corridor via vibrotactile feedback (see Figure 4.8).

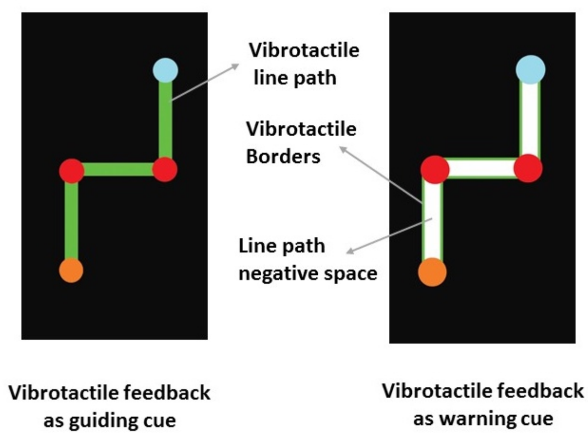

Figure 4.8 Path tracing using vibrotactile lines versus vibrotactile borders

Accordingly, experiment 6 was designed with a two-fold objective: (1) to assess if users can develop an accurate mental representation of the presented spatial path pattern by using vibrotactile feedback as a warning cue, and (2) to empirically measure the minimum interline-gap width that best supports line tracing and integration of individual line segments into a globally coherent spatial image of the presented spatial path patterns.

4.4.1 Method

Participants. Eighteen blindfolded-sighted participants (8 females and 10 males, ages 18-28) were recruited for this experiment. Similar to experiment 4 & 5, eight additional blind and visually-impaired (BVI) participants (3 males and 5 females, ages 24-74, BVI demographic details are presented in Appendix A-Table A.5.) were recruited for a formative assessment.

4.4.2 Stimuli and Apparatus

The structure and complexity of the four spatial path patterns used here were all similar to exp 6 (as shown in figure 4.9). The only difference in the stimuli was that the paths (as shown in figure 4.8) were rendered as a gap ('off' signal) between two bounding vibrotactile borders ('on' signal). Since the purpose of the borders are meant only to be an alert (i.e., detection task), a border width of 1mm (based on findings from experiment 1) was adopted for this design.

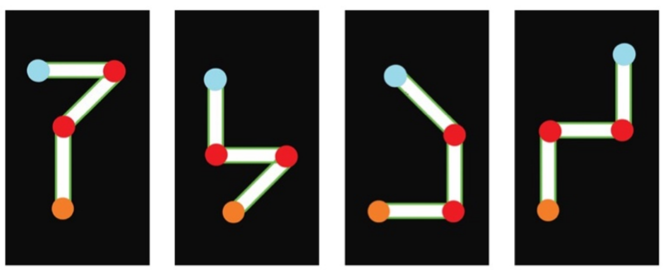

Figure 4.9 Experimental stimuli for interline path tracing: Four different path patterns

The actual path width (i.e., interline gap width) was adopted from experiment 6, except for the 1mm width, as findings from experiment 2 suggested that vibrotactile lines (borders in this case) should be separated by a gap width of 2mm or more to support discrimination at the least of 75% accuracy. Accordingly, 5 different gap widths (i.e., the negative stimulus gap between the two vibrotactile borders) were adopted for this study. Together, the stimulus set comprised 5 gap widths starting from 2mm and increasing by a factor of 1 up to 6mm. Surprisingly, during pilot runs it was found that for the 2 and 3mm gap widths, participants were unable to differentiate/identify the two borders that were comprised of 1mm widths. As discussed in section 3.4, this masking of the gap could be due to the

spurious haptic perception caused by a system delay in triggering the vibratory feedback. Hence, to increase their saliency, a 2mm border width was adopted for the 2mm and 3mm interline gaps and a 1mm border width for the remaining three interline gaps. Furthermore, to evaluate the impact of having different border widths, the 4mm gap width was considered twice: (1) with 1mm borders, and (2) with 2mm borders. The 5 and 6mm gap widths were not included for this border width comparison, as 2mm borders would eventually increase the aggregate width beyond 8mm (a value known to consume excessive screen space based on previous work [Palani 2013; Giudice et al. 2012]). Consequently, the final stimulus set was comprised of 6 different combinations of gap and border widths (2:2, 3:2, 4:1, 4:2, 5:1 and 6:1). The 6 gap and border width combinations along with the 4 path patterns (see Figure 4.8) were all balanced across the 24 pattern matching trials. The apparatus and set-up (i.e., path patterns, vibratory, and auditory feedback) were the same as in experiment 6. The only difference was that the gap was not indicated through any cues; instead, constant vibrotactile feedback was provided, based on the UHL effect "Engine1_100" (i.e., 250 Hz with 100% power) was used to indicate the path borders.

4.4.3 Procedure

The study followed a within-subjects design where each participant performed 24 path learning trials (resulting in 108 observations for each pattern and 72 observations for each tested gap:border combination). In each trial, participants were asked to trace the spatial path once from the start point to the end point by staying within the two borders. Upon reaching the end point, the device was removed. Participants then performed a pattern matching task where they were asked to identify the just-learned spatial path from three geometrically similar alternatives embossed on hardcopy paper. Following the same design as exp 5, the time taken to trace the entire path pattern, the time spent on individual line segments, the time spent on vertices, and the accuracy in pattern matching was compared as a function of 4 patterns, 6 gap:border combinations and 2 participant groups (sighted versus BVI).

4.4.4 Results and Discussion

Unlike experiment 5, the path tracing time increased as a function of increasing gap width (See Figure 4.10). A repeated measures ANOVA revealed that the tracing time differed significantly as a function of the gap widths (F (4, 355) = 3.4237, p < 0.01) and that the path tracing was significantly faster with path made of 2mm borders as compared to 1mm borders (F(1, 430) = 6.60, p < 0.01). With respect to matching accuracy, all six gap:border combinations exhibited above 95% matching accuracy, suggesting that participants were able to accurately develop a mental image of the perceived path pattern. The time spent at angled-vertices was similar to the results from experiment 5, with participants spending significantly (p<0.05) more time at vertices comprised of acute-angles (M = 14.07sec) than at obtuse-angles (M = 10.78sec) or right-angles (M = 8.06sec). The time taken for tracing horizontal, vertical and slanted line segments were all significantly different from each other (F(2, 807) = 3.870, p < 0.05), with tracing of horizontal segments being the fastest and slanted lines as the slowest. As with experiment 5, these differences could be attributed to the ergonomics of hand and finger positions.

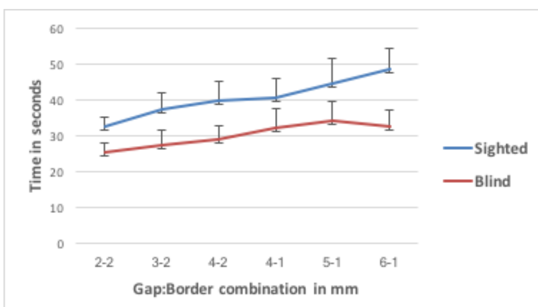

Figure 4.10 Tracing time as a function of gap:border widths and participant groups

Gap:border widths (mm)	Sighted		Blind	
	Mean	SD	Mean	SD
2-2	32.36567	17.316975	25.18766	10.343877
3-2	37.06954	23.521407	27.23922	14.106367
4-2	39.71976	39.585541	29.02172	15.407677
4-1	40.31281	29.635404	31.99231	16.27907
5-1	44.50122	29.183822	34.10178	20.028749
6-1	48.33757	38.764066	32.457	18.111468

Table 4.2. Mean gap tracing time and standard deviation as a function of two participant groups

Post-hoc paired sample t-tests based on Bonferroni correction between gap widths showed that the path tracing time with 2mm and 3mm gap widths was significantly faster than that of the other three gap widths (all ps < 0.05). This is contrary to the results from exp2, which suggested 4mm and above as the minimum interline gap for supporting discrimination of vibrotactile lines. This means, trials with 4, 5, and 6mm gaps should have exhibited better performance when compared to 2 and 3mm gap trials. To investigate this further, the finger traces (based on the device log of user finger trajectories on the touchscreen) were analyzed and it was found that participants spent significantly more time outside the borders as compared to the interline gap ($t(359) = -3.016$, $p < 0.003$). This suggests that, despite being deliberately instructed to stay within the two bounding vibrotactile lines and to use the vibration as a warning cue, participants relied primarily on the vibrotactile lines (i.e., borders) and scanned the path staying out the intended path (i.e., interline gap). This reliance on vibrotactile borders explains the poor performance with 4, 5, and 6mm gap trials as the borders for these trials were rendered at 1mm widths as opposed to the 2mm wide borders used in 2 and 3mm gap trials. In addition to the wider borders, the 2 and 3mm gaps were a subthreshold for discrimination (as found in exp 2), meaning that there was a higher chance of users perceiving the two bounding lines as one vibrotactile line. It is interpreted here as that participants were tracing the paths made of 2-2 and 3-2 gap:border combinations as a line-based paths (i.e., ignoring the interline gaps and treating them as 4mm and 5mm line-paths) similar to how they traced the paths in experiment 5. To add support, the mean tracing time of 2-2 and 3-2 gap:border combinations here is similar to that of the 4 and 5 mm line widths tested in Exp-5. Together, findings here suggest that participants rely on vibrotactile feedback as a guidance cue even when instructed (and designed) to use them as a warning cue. Similar to exps 4 & 5, BVI participants exhibited superior path tracing performance (see Table 4.2 and figure 4.10). Taken together, findings here, in conjunction with results from exps 4 & 5, suggest that vibrotactile feedback is best implemented as a guidance cue. If the

situation demands implementation as a warning cue (e.g., to depict walls of a room), then a minimum width of at least 2mm should be maintained for supporting detection of the bounding vibrotactile lines.

4.5 Summary

The motivation for Phase II of this dissertation research was to establish the spatio-cognitive characteristics pertinent to touchscreen-based non-visual learning. The evaluations studied key spatial constructs such as line-orientation (i.e., horizontal, vertical, or slanted) and the connectivity between different lines (i.e., vertices and the angle formed by these vertices) that form a wide range of graphical materials, such as maps, charts, geometric shapes, and graphs. Findings from three studies (exps 4-6) established key perceptual characteristics for rendering graphical lines and that participants were able to efficiently trace, learn, and build accurate mental representations of presented spatial information. Based on the experimental observations and findings, the following guidelines are recommended for use of vibrotactile cues on touchscreen-based non-visual interfaces:

(1) Findings from experiment 4 suggested that vibrotactile lines should be rendered at a width of at least 4mm for supporting tasks that require tracing of vibrotactile lines on touchscreen devices,

(2) Angular accuracy from experiment 4 suggested that users can accurately judge vibrotactile line-orientation (as low as 7°). Building on this finding, it is suggested here that schematization of oriented lines for non-visual vibrotactile use on touchscreen interfaces does not have to adhere to the traditional 8-sector model [Graf 2013], which suggests rendering of oriented lines at a 45° interval (or the 16-sector model with a 22.5° interval). Instead, oriented vibrotactile lines can be rendered at intervals as low as 7°, provided the lines are of a width of 4mm and are separated from an adjacent line by a gap of 4mm,

(3) Findings from experiment 5 revealed that users find it difficult to trace vibrotactile lines rendered at oblique orientations as compared to horizontal or vertical lines. Schematizing oblique lines to cardinal or ordinal orientations will reduce the cognitive effort associated with

line-tracing. However, if task demands quantitative precision, then it is suggested that the user be provided with supplementing audio/speech cues for supporting tracing of oblique lines.

(4) Findings from experiments 5 and 6 revealed that participants prefer to use vibrotactile feedback as a guiding cue and that this will lead to better line tracing performance. Hence, it is suggested here that the vibratory feedback mechanism is best used as a positive-guiding cue for enhancing the overall usability of touchscreen-based haptic information access.

5. USABILITY OF THE DESIGN GUIDELINES IN SUPPORTING SPATIO-BEHAVIORAL TASKS

This chapter covers Phase III of this dissertation research aimed at validating the usability of schematizing graphical elements based on the guidelines established from Phases I & II. A human behavioral study was conducted to assess whether rendering schematized graphical elements on the vibro-audio interface supports users in the development of an accurate cognitive map and in performing subsequent spatio-behavioral tasks. By comparing performance across three spatio-behavioral measures (i.e., wayfinding, allocentric pointing, and map reconstruction), the study established two key findings. First, the study validated that schematizing graphical elements based on the guidelines established from the phase I and II research and using them with the VAI leads to development of an accurate cognitive map. Second, the results revealed that the cognitive map developed after learning from the VAI is functionally equivalent to that formed after learning from two well-established gold-standard approaches (i.e., a visual interface and a hardcopy tactile interface).

5.1 Generating Perceptually-Salient and Cognitively-Valid Non-Visual Graphical Lines for Vibrotactile Access on Touchscreen Devices

Any graphical representation of a real-world spatial environment will encompass some level of abstraction, rotation, and distortion. For instance, the world is a 3-D spherical object, which is often projected for use as a 2-D map. Depending on the projection system employed, the underlying spatial information will be abstracted, rotated, and/or distorted for ease of use in practical situations. *Google Maps* is a well-known example that employs Mercator projection, which preserves angles but not the fidelity of an area [Ramm et al. 2010]. Preserving certain spatial characteristics at the cost of loss (or degradation) of others is essential for developing spatial products that are aimed at supporting real-world spatial tasks (e.g., positioning, orientation, navigation, etc.,). Understanding this trade-off between preserving key spatial attributes at the cost of loss of others is particularly crucial for the

generation of graphical materials intended for use by blind and visually-impaired users, owing to the sparse spatial resolution of touch. Acknowledging this trade-off, several guidelines have been established (as discussed in Chapter 2) for abstracting, schematizing, and generating tangible equivalents of visual graphics such as raised-line drawings [Braille Authority of North America 2010] and tactile maps [Graf 2013; Rowell and Ungar 2003b; Rowell and Ungar 2003a]. However, as described in chapter 2, these established guidelines are applicable only to tangible graphical output perceived through traditional pressure-based information extraction techniques. As such they cannot be adopted for digital rendering of graphical elements on touchscreen-based non-visual interfaces due to the underlying perceptual and spatio-cognitive differences between accessing graphical elements using pressure-based cutaneous stimulation versus relying on extrinsic vibrotactile stimulation on touchscreen displays. To address some of these challenges, Phase I & II of this dissertation research established a set of design guidelines for rendering perceptually-salient and cognitively-valid graphical lines on touchscreen interfaces. As stated earlier, implementing the guidelines from Phase I and II will not preserve all the spatial characteristics of the original visual graphical elements. For instance, consider schematizing oriented lines based on a cord length of 4mm (as found from exp3). If the oriented lines on the original visual graphic are below the threshold of 4mm, then the original angle subtended by two oriented lines will not be preserved after schematization. However, this loss in original fidelity is necessary in order to ensure that the rendered element is perceptually-salient and has functional utility when implemented in non-visual interfaces such as the VAI. By contrast, if the situation demands preservation of the original angle (e.g., identifying the absolute angle to solve a geometry problem) at the loss of perceptibility (i.e., rendering the lines at a sub-threshold gap), then, the user should be informed of the constraint and provided with additional cues (e.g., speech output saying the actual angle) for extracting the same spatial information. Germane to Phase III of this dissertation research, the evaluations are focused on whether schematizing graphical elements based on the guidelines

established from Phases I & II actually support development of an accurate cognitive map of presented graphical information. Meaning, the visual-to-haptic schematization will preserve the global spatial structure and topology of the graphical elements but not necessarily the quantitative/metric characteristics of the original visual rendering. For any non-visual access solution (such as the VAI) to be truly useful, the schematized graphical elements should not only facilitate development of an accurate cognitive map but should also support efficient spatial behaviors, including tasks that require mental computation, rotation, and manipulation of the cognitive map. Earlier evaluations with the VAI in Phases I and II have demonstrated that users can extract, learn, and build an accurate mental spatial image of on-screen rendered spatial information. However, the testing tasks (i.e., orientation judgments or matching of path patterns) that were evaluated did not require mental computation, rotation, or manipulation of the spatial image. As such, the earlier findings and the established guidelines are valid for spatial cognition tasks but are not generalizable for subsequent spatial behavioral tasks involving computation, rotation, manipulation, and inferencing. Accordingly, experiment 7 was designed to evaluate whether schematizing graphical materials based on the guidelines from Phases I & II and rendering them for use in the vibro-audio interface actually leads to development of an accurate cognitive map that supports common spatio-behavioral tasks.

5.2 Experiment 7: Validating Design Guidelines and Demonstrating Usability of the Vibro-Audio Interface in supporting Spatio-Behavioral Tasks

As stated in section 1.2, several non-visual graphical access solutions have failed to address the long-standing graphical access problem due to various shortcomings, such as expense, time to produce, non-portability, and lack of ability to render graphics in a dynamic manner [Giudice et al. 2012; O'Modhrain et al. 2015; Samuelson and Zeckhauser 1988; Elli et al. 2014]. It is postulated here that these shortcomings are not the only reason that the extant solutions have not reached the intended BVI demographic. For instance, mouse-based haptic devices, such as the Virtouch, are capable of dynamic

presentation of non-visual information and are relatively cheap but suffer from a cumbersome authoring process and non-portability. Similarly, there are pros and cons to all of the existing non-visual graphical access solutions. While the cons are an obvious reason for the failure of such solutions, it is argued here that the lack of demonstration of their unique pros is equally attributable to why these solutions have not been successful in reaching the target end-users. As stated in section 1.2, the evaluation of most of these graphical access solutions have shown efficacy in a usability context or on their technological merits but have failed to demonstrate an actual advantage of using the solution in relation to well-established approaches. As such, BVI individuals may opt for the status quo, even if not optimal, until there is a clear demonstration of the advantages of new approaches relative to reliable, familiar, and tested aids, such as traditional hardcopy tactile graphics [Samuelson and Zeckhauser 1988; Wilson 2000]. Although the guidelines established from Phases I and II of this research were based on valid scenarios, it cannot be interpreted that rendering graphical elements on the VAI based on these guidelines will be sufficient to solve the long-standing graphical access issue or that it will be readily adopted by the target end-users. The vibro-audio interface advanced in this dissertation could also face the same pitfalls as the extant graphical access solutions if we fail to demonstrate its advantages in relation to well-established approaches to graphical access. Accordingly, experiment 7 was motivated by the two goals:

(1) to validate whether schematizing graphical elements based on the guidelines established from Phases I & II and rendering them for use with the VAI supports the development of an accurate cognitive map and subsequent spatio-behavioral tasks, and

(2) to demonstrate the advantages and limitations of the current approach (from point 1) in relation to well-established and tested traditional graphical access approaches (i.e., visual graphics and hardcopy tangible graphics).

The two goals were addressed through a map learning and spatial behavioral task comparing performance between three different learning modes: (1) the vibro-audio interface, (2) a hardcopy raised tangible interface, and (3) a visual interface. By comparing performance across spatio-behavioral test measures that demand computation, rotation, and inferencing of the ensuing cognitive map, we can interpret whether the cognitive map developed in the VAI-condition is similar/better/worse when compared to that of the cognitive maps developed from the visual-condition and the hardcopy-condition. The logic here is that the level of learning in each condition is controlled (via a learning criterion test) and the accuracy of the developed cognitive map is compared across the three learning modes through subsequent performance on a common set of spatio-behavioral tasks. If the performance with the VAI is similar/better than the other two conditions, it would affirm that the vibro-audio interface (with graphical elements rendered based on the guidelines from Phase I and II) is a viable approach that is functionally equivalent to that of the well-established approaches. By contrast, if the observed performance is found to reliably differ between the conditions, with the VAI leading to significantly worse performance, then further investigations must be carried out to identify the reason for the differences, with the goal of mitigating them accordingly.

5.2.1 Method

Participants: Sixteen blindfolded-sighted participants (8 females and 8 males, ages 19-32) were recruited for this experiment. It should be noted that the study was intended as a proof of concept and as discussed in section 4.1.1, use of blindfolded-sighted participants is reasonable here and is widely accepted in the efficacy testing of assistive technology [Sears and Hanson 2012].

5.2.2 Stimuli and Apparatus

The stimulus set consisted of four different network-style maps (i.e., nodes and links). Each map was designed to represent a real-world environment (e.g., tracks and stations of a metro train(s),

rooms/stores along the corridor layout of a building/shopping mall, and landmarks along the road on a transit map).

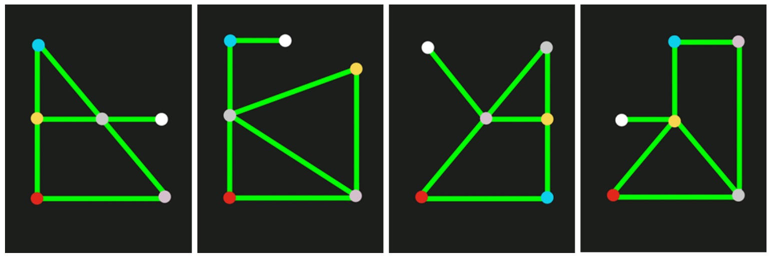

Figure 5.1. Experimental maps rendered on the Samsung galaxy tab3 android tablet.

Each map was composed of a fixed start location, four landmarks and a dead-end that were all connected by seven line segments. All four maps had the same level of complexity but different topology (see figure 5.1). The complexity was matched in terms of both number and position of spatial components: that is, each map had exactly seven line segments, four landmarks, one dead-end, three 2-way junctions, one 3-way junction, and one 4-way junction. In terms of spatial position, the overall width and height of the global structure of the map, the start location, and the horizontal line segment from the start location was matched across all four maps.

All maps were rendered using a Samsung galaxy Tab-3 Android tablet. The graphical lines (e.g., road/transit-path/corridors) were rendered at a width of 4mm (as was established from exps 2, 4, & 5). The scope of this work (see section 1.2.2) is primarily on rectilinear line-based graphical elements and accordingly the intersections were considered as a region and rendered as a circle (0.5-inch radius). As was discussed in section 3.4, a 'circling' exploration strategy is the common exploratory procedure (EP) used for identifying intersections and the lines emanating from it. Since the intersections here are of size 0.5-inch radius, performing the 'circling' EP would mean that the circle formed by users' tracing behavior will always be bigger than the 0.5-inch radius. Based on this logic, oriented lines were separated at an angle greater than 18° (which corresponds to a cord length of 4mm as established in exp 3). In addition, each map also had at least one pair of landmarks that was aligned horizontally and another pair aligned

vertically. Such alignments are critical for supporting efficient navigation and wayfinding. For instance, the entrance and exit are often aligned in many buildings to facilitate easy and quick navigation. In addition to the experimental maps, two smaller maps (each with 3 landmarks and 4 line segments) were designed for use in a practice session.

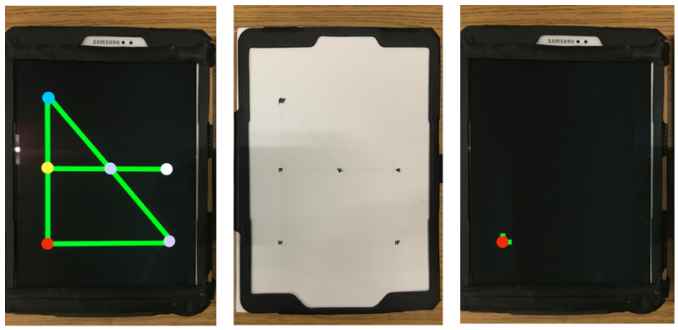

Figure 5.2. Experimental maps in three learning mode conditions: VAI (left), Hardcopy tactile interface (center), Visual interface (right).

5.2.3 Conditions

Three learning-mode conditions were designed and evaluated for this study: (1) the vibro-audio interface, (2) a hardcopy raised tangible interface, and (3) a visual interface. All three conditions were matched in terms of their spatio-temporal integration. That is, in all three conditions the field of view (either via touch or vision) was limited to the size of the contact finger digit (~0.35 inch). In all three conditions, participants were allowed to use only one finger for exploring the maps in a sequential manner. *Figure 5.2.* illustrates this design by presenting an experimental stimuli across the three learning-mode conditions.

For the VAI condition, vibrotactile feedback was generated from the device's embedded electromagnetic actuator, i.e., an off-balance motor, which was controlled within the application script. Similar to the design of experiments 5 & 6, the lines rendered were given a constant vibration - an infinite repeating loop at 250Hz with 100% power, while the regions were given a pulsing vibration – an infinite repeating loop at 250Hz switching between 75% and 100% power. In addition, the regions were

also indicated via a continuous audio cue (i.e., sine tone) and a speech output saying the name of the landmarks such as “Start”, “Dead-End”, “Logan Airport”, “Macy’s”, etc. The user’s finger movement behavior was tracked and logged within the device and used for measuring learning time and analyzing tracing strategies.

For the hardcopy conditions, tactile analogs of the same stimuli were produced on Braille paper, using a graphics embosser (ViewPlus Technologies, Emprint SpotDot). The paper was then mounted on the touchscreen of the Galaxy tablet device (see Figure 5.2) such that auditory information could be given in real-time, thereby matching the available information content with the vibro-audio interface. This also facilitated logging of user’s finger movement behavior and for measuring learning time and analyzing tracing strategy.

For the visual condition, the visual feedback of the graphical information was provided through a narrow viewing window (of size 0.35 Sq. Inch) that appeared above the participant’s finger contact location on the screen (see figure 5.2). This provision was done to limit the visual field of view and to enforce sequential learning with visual access so it to matched the available information with the other two conditions. The auditory feedback was similar to the other two conditions but no extrinsic haptic (vibration) feedback (except for feeling the device’s glass screen) was provided in this condition. Similar to the other conditions, the user’s finger movement behavior was logged within the device and used for measuring learning time and analyzing tracing strategies.

5.2.4 Procedure

The study followed a within-subjects design with participants running in each of the three learning-mode conditions. In each condition, participants learned one map and performed the same subsequent testing tasks. The condition orders were counterbalanced between participants, and the maps were randomized between conditions. Each condition consisted of a training phase, a learning phase, a learning-criterion test, and a testing phase.

Training Phase**:** Each of the three conditions began with two training trials, in which the experimenter explained how to use the learning mode for that particular condition, their learning goals and how to perform the testing tasks. In the first trial, participants explored a practice map, with corrective feedback given as necessary. They were instructed to visualize the network map as being analogous to a real-world map (such as a subway map or hotel floor layout depending on the landmarks). For instance, map-1 was designed to mimic the Boston metro and accordingly had landmarks such as *Logan Airport, Harvard Square, South Station*, etc. The experimenter then conducted a mock test-phase to demo the testing tasks that would be used during the experimental trials. In the second training trial, participants were blindfolded (except for the visual condition) and were asked to learn an entire practice map. Once the participant indicated completion of learning, the experimenter conducted a practice test-phase (see testing procedure in the following section). The experimenter evaluated the testing tasks immediately and gave corrective feedback as necessary in order to ensure participants fully understood the tasks before moving on to the actual experimental trials.

Learning Phase: During the learning phase, participants were first blindfolded (except for the visual condition) and were asked to use the index finger of their dominant hand for exploring and learning the map. The experimenter then placed the participants' primary finger at the start location and instructed them to freely explore and learn the entire map. The names and number of landmarks were not given to them ahead of time, as this was evaluated during the learning-criterion test. Participants did not have any restriction on their hand movements or exploration strategies. Participants were asked to indicate when they believed that they had thoroughly learned the entire map. This phase was intentionally designed to employ self-paced learning, versus using a fixed learning time, as the focus here was to capture the individual differences in learning behavior with respect to the three learning-mode conditions. Once participants indicated that they had completed learning the map, the experimenter removed the device and asked the participant to verbally report the number of landmarks on the map,

including their names. If participants missed any landmark, they were given an additional 5-minutes time to explore the map again and learn it in its entirety. If they reported correctly, they continued with the testing phase. A correct answer here will confirm that all participants had accessed the entire map in each learning-mode condition and that any difference in testing behavior is not due to lack of information extraction.

Testing Phase: This phase consisted of three tasks: (1) a wayfinding task, (2) a pointing task, and (3) a map reconstruction task.

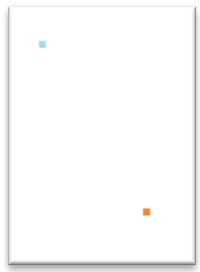

Figure 5.3. Pointing device used in the pointing task (left), A4 Canvas for the reconstruction task with start location (right)

In the wayfinding task, participants were asked to trace the shortest route between two landmarks. For each wayfinding task, Participants were provided with the same map in the same mode they used for learning (i.e., either as the VAI, hardcopy or visual, depending on the map learning condition). The experimenter then placed their dominant index finger at one of the landmarks and asked them to trace the shortest route to a designated target/destination landmark. The landmarks were not indicated via speech output as it was the participants' task to trace the route to a target landmark and indicate its name. Since the task is not focused on localization of actual landmark location, but to trace the shortest path between two landmarks, all the non-line spatial features (i.e., intersections, start, and dead-ends) were indicated via a sine tone but no semantic information was given (i.e., no auditory label). Upon reaching the target location indicated by a sine tone, participants were asked to raise their finger and verbally confirm the landmark name on that location. In each condition, participants performed a set of

four wayfinding trials. All combination of routes were not covered due to time constraints and to avoid potential bias in the other two testing tasks. However, the four trials covered all the six vertices (4 landmarks, a start location, and a dead-end) either as a start or target location.

In the pointing task, participants indicated the allocentric direction between landmarks using a pointer affixed to a wooden board (see Figure 5.3). The pointing task consisted of a set of four pointing trials (e.g., indicate the direction from elevator to lobby). Similar to the wayfinding task, not all pairwise combinations were covered here but all six landmarks were tested (i.e., either pointed from or pointed to) within the four pointing trials. The four pointing trials were intentionally designed such that users must compute knowledge of non-route Euclidean information (i.e., perform mental rotation and computation within their cognitive map) to correctly indicate the direction between landmarks.

In the reconstruction task, participants were asked to draw the map and label the vertices on a template canvas (with grids provided) matching the size of the device's screen. To provide the participants with a reference frame for the reconstruction task, the start point was already indicated within the canvas.

5.2.5 Experimental Measures

From this experimental design, four measures were evaluated as a function of the three learning-mode conditions: learning time, wayfinding accuracy, pointing accuracy, and reconstruction accuracy.

Learning time: All participants cleared the learning-criterion test in the first trial and were thus not required to take additional learning periods. The total learning time was measured from the log files generated in each trial and is defined as the time from the moment they touch the start location until when they verbally indicated that they were confident of their learning of the map. Learning time for the VAI condition was expected to be significantly higher than the other two conditions. This is because the VAI relies on indirect perception of the graphical lines (i.e., associating the extrinsic vibrational feedback with the on-screen graphical line) as opposed to directly seeing the graphical line using visual cues or tactually feeling a physically embossed line.

Wayfinding accuracy was measured by extracting the sequence of users' finger movements (i.e., the path they traced) from the log files generated in each wayfinding trial. There were instances where two landmarks had more than one route option (i.e., an optimal-shortest route and a suboptimal route). Both route options are considered a correct response and were not analyzed separately as there were only two instances (1 each in VAI and visual) where participants traced a suboptimal route. A discrete scoring was applied based on correctness of their response (i.e., 1 if traced correctly, 0 otherwise).

Wayfinding sequence: The sequence of landmarks in the wayfinding trials were compared with the sequences of landmarks covered during the learning phase. This comparison was carried out to assess if the accuracy in wayfinding was supported by spatial inference, computation, and rotation of the ensuing cognitive map. That is, if participants have traced the tested route (e.g., *Airport to Boston college via Harvard square*) during their learning then the wayfinding accuracy in reaching *Boston college from the Airport via Harvard square* could be inferred (and attributed) as matching of mental spatial image from learning to testing. By contrast, if they did not traced the path in the same sequence during learning, then accuracy in the wayfinding task would mean that participants necessarily performed mental computation, rotation, and inferencing of their developed cognitive map to execute the route. A discrete scoring was applied based on whether the sequence in test trials was traced during learning (i.e., 1 if traced during learning, 0 otherwise).

Relative Directional accuracy was defined as the accuracy in performing allocentric pointing judgments between landmarks. Absolute angular errors were measured by calculating the difference between the angles reproduced by the participants and the actual angles.

Reconstruction accuracy was measured by comparing the reconstructed map against the actual map. The comparison was made at two levels: (1) discrete scoring, and (2) Bi-dimensional regression. At first, a discrete scoring (i.e., 1 if correct, 0 otherwise) was applied based on whether participants accurately recreated the global spatial pattern and topology between the lines that construct the map. Following

that, the reconstructed maps were analyzed using *bi-dimensional regression* [Tobler 1994]. For this analysis, six anchor points were selected from each of the maps (i.e., start, dead-end and four landmarks). The degree of correspondence of these anchor points between the actual map and the reconstructed map were then analyzed based on three factors: (1) scale, (2) theta, and (3) distortion index. The scale factor indicates the magnitude of contraction or expansion of the reconstructed map. The theta value determines how much and in which direction the reconstructed map was rotated with respect to the actual map. The Distortion Index is a standardized measure of the overall difference between the reconstructed map and original map [Friedman and Kohler 2003].

5.2.6 Results and Discussion

Measures	**VAI**		**Hardcopy**		**Visual**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Learning time (in seconds)	434.00	190.08	165.00	57.70	100.00	26.04
Wayfinding accuracy (in percent)	94	22	98	18	98	13
Wayfinding sequence (in percent)	32	47	51	50	34	48
Relative-directional error (in angle)	5.89	8.37	7.76	10.74	5.80	8.24
Reconstruction accuracy (in percent)	71	47	85	36	85	36

Table 5.1 Mean and SD for the tested measures as a function of learning-mode conditions

Measures	**df**		***f***	**Sig.**
	Hypothesis	**Error**		
Learning time	2	39	32.86	< 0.001
Wayfinding accuracy	2	165	0.81	> 0.05
Wayfinding sequence	2	165	2.81	>0.05
Relative-directional error	2	165	0.85	> 0.05
Reconstruction accuracy	2	39	0.59	> 0.05
Scale	2	39	0.60	> 0.05
Theta	2	39	1.38	> 0.05
Distortion Index	2	39	0.38	> 0.05

Table 5.2. ANOVA results (f and p value) for each of the tested measures

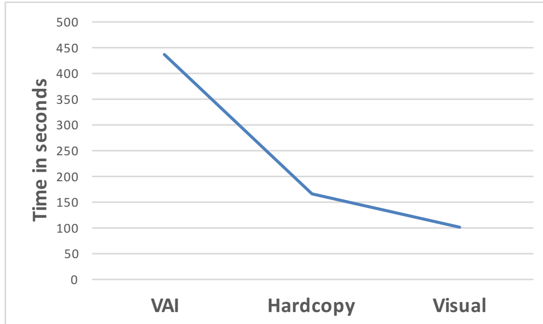

Figure 5.4. Mean learning as a function of three learning-mode condition.

Each of the performance measures were compared using a set of repeated measures ANOVAs across the three learning-mode conditions. The most important findings, as shown in Table 5.1 & 5.2, are the similarity of performance (except for learning time) across the three conditions. As stated earlier, the difference in learning time between the conditions was not surprising as it was expected due to the difference in the extraction methods inherent to each of the three learning-modes. The results here clearly demonstrate that the approach of schematizing line-based maps using the design guidelines established from Phase I & II, and rendering them for use with the vibro-audio interface, leads to development of an accurate cognitive map that is functionally equivalent to well-established hardcopy tangible graphics and visual graphics.

Results from the wayfinding sequence (Table 5.1) has shown that majority of the routes traced during test trials were not traced during learning. In addition, the accuracy in wayfinding trials did not correlate with the instances where the route was traced during learning (r = -0.19, p < 0.001). This clearly suggests that participants were not simply using route memory to perform test trials but were able to perform spatial inference of ensuing cognitive map to accurately trace the route during testing. Similarly, results from the pointing task (i.e., an angular error ~7°) suggest that participants were able to accurately perform mental rotation of the ensuing cognitive map and to compute non-Euclidean directions between landmarks. As shown in Table 5.2, performance in these two measures and the reconstruction

accuracy performance were not reliably different between the three learning-modes. Together, these results suggest that participants were able to build an accurate cognitive map in all three conditions.

On average, participants took ~15 minutes to learn maps of similar complexity in previous studies that used touchscreen-based vibration and auditory cues [Su et al. 2010; Poppinga et al. 2011; Palani and Giudice 2014; Palani et al. 2016]. By comparison, the average learning time was ~7 minutes in this study (see Table 5.1 and Figure 5.4) with maps that were larger and complex than the maps used in the previous studies. The key difference here is that the maps used in the previous studies were not optimized based on perceptual parameters or spatio-cognitive design guidelines, as were evaluated in the current study. These findings clearly suggest that the schematization of graphical elements based on guidelines established in the Phase I and II research significantly reduce the learning time and by extension, reduce the cognitive effort imposed while learning via this new form of access technology. Similarly, the mean pointing error of ~5.89° for the VAI condition was numerically lower than the hardcopy conditions (i.e., mean error of ~7.76°) and is significantly lower than the errors reported (i.e., in the range of ~18°) in previous studies with touchscreen-based haptic interfaces [Palani and Giudice 2014; Palani et al. 2016; Palani and Giudice 2017]. These findings clearly validate that the design guidelines (based on Phase I and II) implemented on the prototype VAI has positively influenced user performance, both in learning and in their resulting spatial behaviors.

5.3 Summary

This chapter detailed the Phase III research of this dissertation that aimed to validate the design guidelines (established in Phase I and II). Results from a human behavioral study revealed that schematizing line-based maps using the design guidelines from Phase I & II, and rendering them for use with the vibro-audio interface leads to development of an accurate cognitive map that is functionally equivalent to well-established hardcopy tangible graphics and visual graphics. As stated in section 4.1, learning from different modalities (i.e., vision and touch) can all lead to the development of an amodal

spatial representation in memory, which support subsequent spatial behaviors in a functionally equivalent manner [Avraamides et al. 2004; Giudice et al. 2011]. While this was established for traditional tangible graphics, results here clearly support this theory and extend the evidence for amodal representations built up from learning from touchscreen-based vibrotactile graphical information access. Overall, the current results, based on the tested measures (i.e., learning time, wayfinding accuracy, wayfinding sequence, relative directional accuracy and reconstruction accuracy) provide compelling evidence that using schematized graphical elements on the vibro-audio interface, as is advanced in this dissertation research is a viable approach for providing haptic (vibrotactile) access to graphical information rendered on touchscreen-based displays. The next chapter provides an expanded discussion of the implications of these findings and the application for their use in the design of touchscreen-based non-visual information access solutions.

6. KEY FINDINGS, CONTRIBUTIONS AND DIRECTIONS FOR FUTURE RESEARCH

Lack of access to graphical information has had huge negative consequences on the educational, vocational, navigational, and social needs of millions of blind and visually-impaired (BVI) people. This dissertation research was driven by an interest to address this long-standing graphics access problem among BVI people. Specifically, the focus was to provide a deeper scientific understanding of the underlying non-visual graphical problem and to address it through development of a viable touchscreen-based graphical access solution, called a vibro-audio interface (VAI). The underlying challenge of non-visual graphical access was postulated in this dissertation as primarily stemming from the disconnect between three research domains, which the research aimed to bridge in a unified sequence of studies. These three domains included:

(1) ***Foundational theoretical research*** that focuses on touch perception, sensory substitution, and theories from spatial science.

(2) ***Technological research*** that emphasises touchscreen interface design, multimodal interaction design, and Human-Computer Interaction design.

(3) ***Usability research*** that evaluates user acceptance, behavior, efficacy, advantages/disadvantages, and generalizability of a new interface/approach*.*

To overcome the pitfalls of traditional graphical access approaches, this dissertation research adopted an interdisciplinary approach that borrowed from and connected each of the domains in a manner that was best served to address the questions of interest.

This research builds on the evidence from our previous work that established touchscreen-based devices as a viable option for conveying digital graphics to BVI users via haptic and/or audio cues [Palani 2013; Giudice et al. 2012]. Although promising, they also poses unique and novel challenges due to the limitations imposed by: (1) lack of fundamental theoretical research on touchscreen-based haptic

perception and spatial cognition, (2) lack of usability research on touchscreen-based non-visual learning of graphical information and subsequent user behaviors, and (3) lack of technological research evaluating the hardware/software limitations of these systems in the context of non-visual graphical accessibility. For a touchscreen-based graphic access solution to be functional, it is essential that the underlying graphical renderings are schematized to accommodate the perceptual and cognitive characteristics pertinent to touchscreen-based haptic information access. Building on the interdisciplinary approach connecting the three domains, this dissertation established a set of core perceptual parameters and design guidelines aimed at advancement of touchscreen-based graphical access approaches. A new testing paradigm, called a psychophysically-motivated usability evaluation, was developed to guide this dissertation research towards empirical identification of the core perceptual parameters. Employing this new evaluation approach, a three-phase research program was conducted with the unified goal of developing a viable graphical access solution. The three research phases were driven by a logical progression of seven research experiments. The following synopsis summarizes the key findings and the principle scientific contributions that were generated as outcomes of each research phase of this dissertation.

6.1 Empirical Identification of Perceptual Parameters and Guidelines

This dissertation contributed novel concepts pertinent to touchscreen-based vibrotactile perception and filled an important gap in the literature on vibrotactile touch perception characterizing design and implementation of graphical stimuli rendered on touchscreen devices. For touchscreen-based solutions to support non-visual graphical access via vibrotactile feedback, it is a pre-requisite that the presented graphical information is schematized based on: (1) the perceptual specificity of touchscreen-based vibrotactile feedback, and (2) the technical limitations of the interface that demands active exploration using just one finger for information extraction. To perform such schematization, it is necessary to first identify the core perceptual parameters that support detection and discrimination of different graphical

elements. Towards this end, three psychophysically-motivated usability experiments were conducted as part of Phase I research that established three key perceptual parameters:

(1) Results from Experiment 1 suggested a minimum vibrotactile width of 1mm for supporting accurate detection of vibrotactile line,

(2) Results from Experiment 2 revealed that the ability to accurately discriminate parallel vibrotactile lines is not only dependent on the width of the interline gap but is also dependent on the actual width of the bounding vibrotactile lines. Accordingly, a 4mm interline-gap bounded by 4mm vibrotactile lines is recommended here as the minimum widths for discriminating parallel vibrotactile lines.

(3) Results from Experiment 3 recommended a minimum angular separation of 4mm for discriminating oriented vibrotactile lines. Findings also suggested that designers must understand the dependency between angle, radius, and cord length and schematize the angular elements by calculating the minimum perceivable angle (using the formula: $\theta = 2 \arcsin(\text{cord length}/2r)$) based on a minimum 4mm cord length.

Of importance, all three parameters were not only identified to provide perceptual saliency based on psychophysical procedures (i.e., a forced choice response rate of at least 75% accuracy), but were determined based on its ability to support functional usage in practical scenario and enhance overall usability of the evaluated vibro-audio interface. In addition to the perceptual parameters, the outcomes from these three experiments add to the corpus of experimental evidence supporting similarity between blindfolded-sighted and BVI users. In particular, results from these studies demonstrate that the ability to access, learn, and mentally represent graphical material without vision via vibrotactile feedback is highly similar between blindfolded-sighted and blind and visually impaired participant groups. This finding adds support and validity for the growing evidence that using blindfolded-sighted participants is

a reasonable sample in the testing/evaluations of touchscreen-based non-visual interfaces [Sears and Hanson 2012; Shneiderman et al. 2009;Palani 2016; Palani 2017].

Building on the perceptual parameters established from Phase I, Phase II of this dissertation studied key spatial constructs such as line-orientation (i.e., horizontal, vertical, or slanted) and the connectivity between different lines (i.e., vertices and the angle formed by these vertices) that in combination, represent a wide range of graphical materials, such as maps, charts, geometric shapes, and graphs. For comprehending these spatial products, user should perform a *line tracing* behavior in addition to *detection* and *discrimination* of individual line segments as was evaluated in Phase I. In Phase II of this dissertation, three new psychophysically-motivated usability experiments (4, 5, and 6) were conducted that established the core spatio-cognitive characteristics pertinent to accessing, learning, and apprehension of spatial information rendered as vibrotactile lines on touchscreen-based devices. Results from these studies led to three key findings: established three core design guidelines:

(1) a minimum vibrotactile width of 4mm is necessary for supporting tasks that require tracing of vibrotactile lines, judging line-orientation and learning of complex spatial path pattern (Exp 4 & 5). Findings also revealed that.

(2) When rendered at a linewidth of 4mm, users can accurately judge vibrotactile line-orientation to an interval of 7° (Exp 4), and

(3) Participants prefer to use vibrotactile feedback as a guiding cue and that this will lead to better line tracing performance as opposed to using them as a warning cue (Experiment 6).

Finally, Phase III of this dissertation evaluated whether schematizing graphical elements based on the parameters and guidelines established from Phases I & II actually support development of an accurate cognitive map of presented graphical information. Evaluations in Phase III were not only focused on

perception and cognition, but also evaluated whether learning via this new form of information access technology actually supports subsequent spatial behavioral tasks involving spatial computation, rotation, and inferencing. In addition, experiment 7 also evaluated the advantages and limitations of the vibro-audio interface in relation to well-established and tested traditional graphical access approaches (i.e., visual graphics and hardcopy tangible graphics). The testing tasks in this experiment were intentionally designed to demand mental rotation (e.g., allocentric pointing), spatial computation (e.g., wayfinding and map reconstruction), and inferencing of the ensuing cognitive map (e.g., wayfinding and map reconstruction). By comparing the VAI with two well-established graphical access approaches (visual graphics and hardcopy tangible graphics), results revealed that schematizing line-based maps using the design guidelines established from Phases I & II, and rendering them for use with the vibro-audio interface leads to development of an accurate cognitive map that is functionally equivalent to those built up from learning with well-established hardcopy tangible maps and visual maps.

6.2 Guidelines for Rendering Perceptually-Salient and Cognitively-Valid Graphical Lines supporting Haptic-Access on Touchscreen Interfaces

A major contribution of this dissertation research is the evidence extending theories pertaining to human perceptual and spatio-cognitive characteristics involved in non-visual access of spatial information. This research fills a significant gap in the domain of blindness accessibility by providing much needed guidance for schematizing, converting (visual-to-haptic) and rendering of haptically (vibrotactile) perceivable graphical renderings on touchscreen-based interfaces. The outcomes of the seven experiments provided six design guidelines for schematizing graphical elements for use with touchscreen-based graphical access solutions. The following list of guidelines does not imply an order for importance.

Guideline 1: *Minimum line width*. For tasks requiring simple *detection* of graphical lines via vibrotactile cuing on touchscreen interfaces, each line should be rendered at a minimum width of 1mm. However,

for supporting *discrimination* and *line tracing*, the vibrotactile lines should be rendered at a minimum width of 4mm. For instance, consider a simple histogram (figure 6.1), where rendering each bar at a width of 1mm will support detection (e.g., counting the number of bars in a graph), but if the task requires users to conceptualize the height of each bar and build a mental representation of the global structure of the graph, then the lines should be rendered at a width of 4mm such that users can perform line tracing behavior. See figure 6.1. for an illustration of visual-to-haptic schematization of a sample histogram based on this guideline.

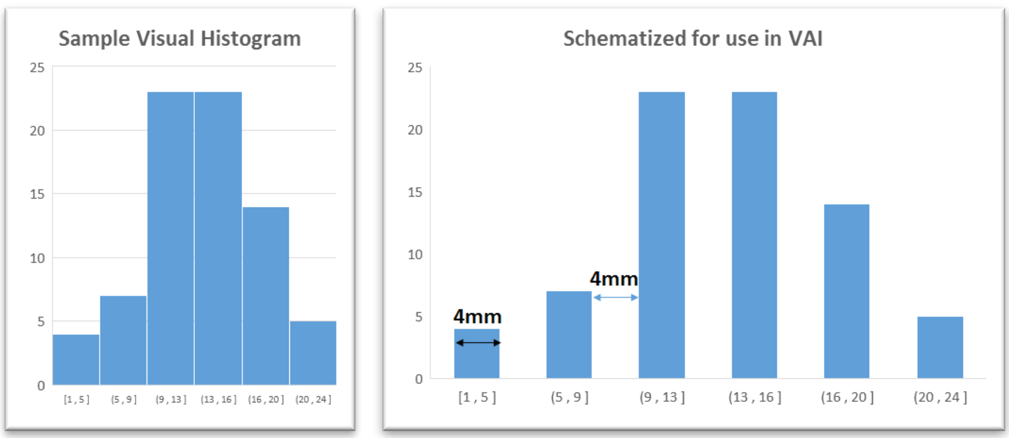

Figure 6.1. (left) An exemplar visual histogram, (right) Variant of the same visual histogram schematized for use in the VAI, where each bar is rendered at a width of 4mm and separated from adjacent bars by an interline-gap of 4mm.

Guideline 2: *Minimum separation.* When rendered parallel to each other on a touchscreen, the vibrotactile lines should be spatially separated with an interline gap of 4mm, which enables each line to be identified as a distinct line. For instance, consider the same example of a histogram from figure 6.1, wherein, if two bars are rendered with an inter-line gap of less than 4mm, there is a high probability that users will incorrectly perceive them as one wide bar. On the other hand, if they are rendered at a gap wider than 4mm, then the stimuli will consume unnecessary screen space without improving accuracy. Adopting wider than a 4mm line is argued here as a bad design choice as the underlying touchscreen device is a limited information density display, which already has relatively limited screen space.

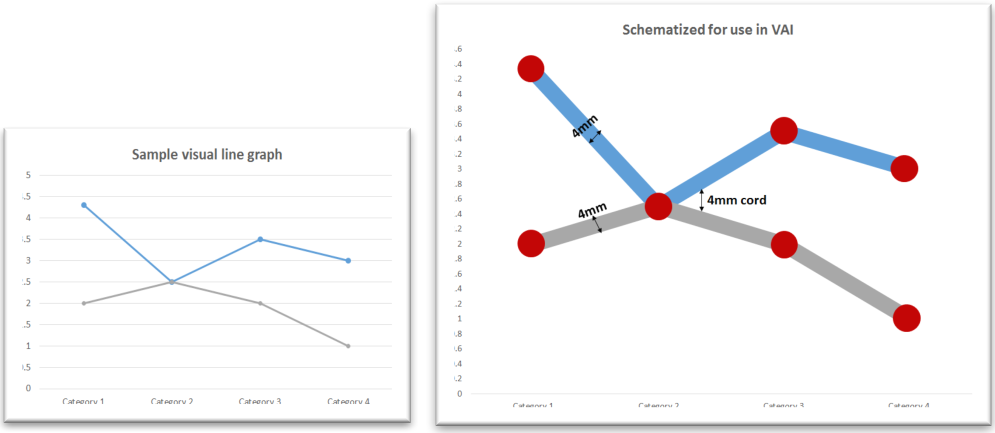

Figure 6.2. (left) An example visual line graph, (right) Variant of the same line graph schematized for use with the VAI, where the lines are rendered at a width of 4mm and the y-axis intervals are increased such that the angular separation between oriented lines could maintain a minimum of 4mm cord length.

Guideline 3: *Minimum angular separation.* Oriented vibrotactile lines should be spatially separated from adjacent oriented lines using a minimum 4mm cord length such that each can be identified as a distinct line while employing the most common ‘circling’ exploration strategy. While schematizing visual graphical materials for use with the VAI, in addition to rendering each line at a width of 4mm, the angular separation between the two oriented lines (i.e., the blue and grey lines that are projecting from the same intersection as in figure 6.2) should be increased to match the minimum perceivable cord length of 4mm. In this line graph example (figure 6.2), maintaining the quantitative precision of each line is essential as the graph is meant to convey quantitative information. Accordingly, the intervals of the y-axis were manipulated to scale up the entire graph such that a 4mm cord length will be maintained between the intersecting lines. By contrast, if preserving such quantitative information is not important (e.g., simply indicating whether a line is inclining or declining), then it is a better practice to simply alter the oriented lines to attain a 4mm cord length. This will not only consume less screen space but will also reduce the time to access and extract the information.

Guideline 4: *Individual Line-Orientation.* The orientation of any schematized vibrotactile lines should remain as close as possible to the orientation of the original graphical line. As shown in figure 6.2, maintaining the line-orientation of the underlying stimuli is crucial for many graphical materials such as line graphs, maps, statistical trends, etc. However, if the line-orientation has to be altered to facilitate haptic perception, a deviation of +/-7° (as found in Exp 5) is acceptable. Altering the vibrotactile line up to +/-7° will lead to a mental representation that is functionally equivalent to original visual line-orientation.

Guideline 5: *Simplified Intersections.* For simplifying intersections on embossed graphics that rely on pressure-based stimulation, traditional guidelines recommend a 8-sector model, that suggest rendering oriented line at 45° interval (or a 16-sector model with 22.5° interval). By contrast, findings from this dissertation research suggest that oriented vibrotactile lines can be accurately perceived when rendered at intervals as low as 7°, provided the lines are of a width of 4mm and are separated from an adjacent line by a gap of at least 4mm. As stated in guideline 3, designers should consider schematizing the intersections based on an understanding of which aspects (i.e., qualitative or quantitative) of the original intersection should be preserved after schematization. If precise quantitative information (e.g., the actual angle subtended between each intersecting line) has to be preserved, then designers should increase the overall size of the rendering to make the gap perceivable. If increasing the size of the graphic is not an option, then it is suggested here that the user be provided with supplementing audio/speech cues (e.g., speech output stating '*a three-way intersection*').

Guideline 6: *Vibration Feedback mechanism.* To maximize the usability of touchscreen-based information rendering and to enhance the vibrotactile feedback mechanism, touchscreen-based vibratory feedback is best used as a positive-guiding cue rather than as a negative-warning cue. If the designers and researchers decide to implement vibratory feedback as a negative-warning cue (e.g., to

show the bounding lines of a region such as walls of a room), then a minimum line width of at least a 2mm border should be maintained for accurate detection and effective tracing of the borders.

These six guidelines are not an exhaustive list for converting and rendering visual graphical lines into haptically perceivable equivalents on touchscreen interfaces. As stated in section 1.3, the guidelines are based on a core graphical component (i.e., rectilinear lines) that serve as building blocks for extending the investigation to other types of graphical components (such as regions, curved lines, points, etc.).

6.3 Eyes-Free Information Access for Sighted Users

Although BVI individuals are the primary end-users for the approach evaluated in this dissertation research, the findings are highly relevant to a much larger user group of sighted people. It is argued here that sighted users could also potentially benefit from accessing information via touchscreen-based vibrotactile feedback. For instance, there are a myriad of everyday applications where visual perception is not possible or needed elsewhere, where sighted people could benefit from nonvisual, touchscreen-based haptic interactions. A typical example is manipulation of an in-vehicle infotainment display (e.g., operating control elements such as menus and buttons) while driving a car. Engaging in this type of multi-tasking behavior can be dangerous and even life threatening as the drivers' visual attention is being shifted from the primary task of seeing the road to accessing control elements on an interface [Swette et al. 2013]. Utilizing vibrotactile feedback either as a primary mode or as a supplementary cue for interaction with such infotainment systems could significantly reduce interaction time, thereby leaving the driver's visual attention focused on the primary task of safely operating the vehicle. Similarly, emergency management situations often require users to access maps and other important visually-oriented spatial information in a non-visual mode due to unexpected loss of light from power outages or for evacuation of a building due to a fire or smoke. Similarly, owing to an explicit need for stealth in covert military operations, users must access information in a non-visual mode as using visual cues could reveal their location to enemies. Incorporating an eyes-free haptic interaction mode for information

access in these situations, as was developed and evaluated in this dissertation, could provide a simple and intuitive non-visual access solution in such scenarios. Indeed, this dissertation contributed towards increasing the usability of touchscreen-based haptic feedback as a novel non-visual interaction style for both input and output operations on touchscreen interfaces. To support eyes-free haptic interactions, it is necessary that the onscreen visual elements (e.g., scroll bars, edges, app icons, etc.,) are schematized based on the guidelines established in section 6.2. The foundational guidelines established here will serve as basic building blocks for the development of new eyes-free applications and will help to drive the design and rendering of more complex information content that can be haptically perceived on touchscreen-based interfaces.

6.4 Directions for Future Research

As stated in section 1.2.2, the scope and subsequent findings of this dissertation are the first step in laying the foundation for a more comprehensive research program pertinent to touchscreen-based non-visual graphical access solutions. During the three phases of this dissertation research, assumptions had to be made for narrowing the scope, including limiting the study to rectilinear graphical lines and evaluating only specific core aspects of the vibro-audio interface. The following sections discuss how these assumptions (and the limitations observed during the experiments) motivate and propose new ideas for future research.

6.4.1 Non-rectilinear Graphical Elements

As stated in chapter 1, the scope of this dissertation research was regulated to rectilinear line (and polyline) features of graphical materials. The findings and the guidelines that resulted from each of the seven experiments were based only on rectilinear line-based graphical information. As such, the established parameters and guidelines cannot be generalized to region-based graphical information (e.g., rooms in a building, pie charts, geometric shapes, etc.,). The outcome of this research should be considered as a first step towards measurable effects of successful visual-to-haptic schematization and

should be extended to empirically identify the parameters and guidelines for region-based graphical materials.

6.4.2 Specificity of Modality

For all the evaluations conducted in this dissertation research, vibrotactile feedback was used as the primary mode for non-visual information access. As discussed in Chapter 2, this design choice was based on the perceptual advantage of touch over audio. Although all the perceptual parameters identified in this work utilized vibration as the primary feedback mode, adopting them to other touchscreen-based extrinsic feedback mechanisms (e.g., audio or electrostatic cues) should be explored more thoroughly in the future. Also, as discussed in chapter 4, audio feedback, speech output in particular, is essential for comprehension of the semantic and non-spatial information components of graphical content. While a few studies have attempted to provide spatial information via audio feedback [Su et al. 2010; Poppinga et al. 2011; Vazquez-alvarez et al. 2010], the approach of substituting vision with audio for communicating graphical information remains a subject in need of future research. Extending the current findings, future research should examine the specificity of these different modalities (touch, audio, and speech) in conveying spatial/non-spatial information. Considering the sensory and cognitive aspects of each of these modalities, research should also identify the optimal modality for conveying each information component.

6.4.3 Creation of Graphical Materials using Haptic feedback

Chapters 1 & 2 extensively discussed the need for providing blind and visually impaired (BVI) individuals with access to graphical materials. The ability to create graphical materials is also a critical aspect for non-textual communication, especially for educational class projects like accessing geometry or chemistry and for art work. However, little research has been done in the area of non-visual content creation by BVI users. This dissertation research utilized vibrotactile feedback as an output mode for

accessing and learning graphical materials using touchscreen devices. Grussenmeyer et al., has studied the possibility of reversing the vibrotactile cuing mechanism to support creation of graphical contents via gestural inputs [Grussenmeyer 2017]. This means, users could perform gestures to create graphical elements (e.g., lines or shapes) and then change the mode to feel the created graphical element using vibrotactile feedback (as opposed to rendering them from within the device, as was studied in the current research). This alternative feedback mechanism of using haptics for both input and output could prove to be a promising content creation solution for BVI users. Further research is needed to expand this promising idea built on the initial set of guidelines established in the current research.

6.4.4 Automation of Visual-to-Haptic Conversion

As was discussed in chapter 2, hardcopy tangible graphics are the most used and well-established solution supporting BVI users with graphical access. However, a major shortcoming of this approach and several other tangible graphic approaches is the process of manual creation/authoring of the tangible equivalents of visual graphics. In addition, involvement of sighted individuals is a mandate in the traditional visual-to-tactile conversion process. These shortcomings have hindered many graphical access solutions from reaching the target end-users. In order for the VAI (as well as other touchscreen-based graphical access solutions) to overcome these shortcomings, the schematization and rendering of haptic equivalents of the visual graphical materials should be automated and performed within the touchscreen device. The outcomes of this dissertation contribute towards such automatic generation of schematized graphical renderings on touchscreen interfaces. It should be noted that the findings and guidelines from this work do not provide a complete set for enabling automatic conversion, but it provides a good foundational basis and direction for future work in this research area.

6.5 Conclusion

This dissertation set out to address the long-standing graphical access issue faced by millions of blind and visually-impaired (BVI) people through development of a viable touchscreen-based graphical access solution. The findings in this dissertation strongly support the need for visual-to-haptic schematization of graphical materials that are adapted based on the intended task, the perceptual and spatio-cognitive abilities of the human end-user, and the display technology. Implementing the guidelines established in this dissertation lay the foundation for a comprehensive research program towards addressing the long-standing non-visual graphical access problem faced by millions of BVI individuals.

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APPENDIX: DEMOGRAPHIC DETAILS OF BLIND AND VISUALLY-IMPAIRED PARTICIPANTS

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)
M	Retinopathy of prematurity	None	18	Birth	18
F	Retinitis pigmentosa	Light Perception	21	Age 7	14
F	Retinitis pigmentosa	None	22	Birth	22
M	Retinopathy of prematurity	None	24	Birth	24
F	Leber's congenital amaurosis	Light Perception	43	Birth	43
M	Leber's congenital amaurosis	Light Perception	40	Birth	40
F	Pathological Myopia	Light/dark perception in right eye, Fuzzy colors	57	Age 42	15
F	Retinopathy of Prematurity	None	74	Birth	74
M	Retinitis Pigmentosa, atypical, with cone dystrophy	Light/dark perception, some functional peripheral	58	Age 25	23
F	Retinitis Pigmentose	Light/dark perception	63	Age 11	52
M	Retinopathy of Prematurity	Light/dark perception	44	Birth	44
F	Retinopathy of Prematurity	Light/dark perception	71	Birth	71
F	Retinopathy of Prematurity	Light/dark perception	56	Birth	56
M	Retinitis Pigmentose	Light/dark perception	63	Birth	63
M	Glaucoma	Light dark perception	21	Age 16	5
F	Unknown	Light/dark perception	29	Age 17	12
F	Congential Cataracts, Glaucoma	Light/dark perception	70	Age 50	20
M	Retinopathy of Prematurity	Light/dark perception	31	Birth	31
M	Retinopathy of Prematurity	Light/dark perception	43	Birth	43
F	Retinitis Pigmentose	Light/dark perception	37	Birth	37

Table A.1. Blind participant information from experiment 1

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)
F	Retinitis pigmentosa	Light Perception	20	Age 7	13
F	Retinitis pigmentosa	None	22	Birth	22
M	Retinopathy of prematurity	None	24	Birth	24
F	Leber's congenital amaurosis	Light Perception	43	Birth	43
M	Leber's congenital amaurosis	Light Perception	40	Birth	40
F	Pathological Myopia	Light/dark perception in right eye, Fuzzy colors	57	Age 42	15
F	Retinopathy of Prematurity	None	74	Birth	74
M	Retinitis Pigmentosa, atypical, with cone dystrophy	Light/dark perception, some functional peripheral	58	Age 25	23
F	Retinitis Pigmentose	Light/dark perception	63	Age 11	52
M	Retinopathy of Prematurity	Light/dark perception	44	Birth	44
F	Retinopathy of Prematurity	Light/dark perception	71	Birth	71
F	Retinopathy of Prematurity	Light/dark perception	56	Birth	56
M	Retinitis Pigmentose	Light/dark perception	63	Birth	63
M	Glaucoma	Light dark perception	21	Age 16	5
F	Unknown	Light/dark perception	29	Age 17	12
F	Congential Cataracts, Glaucoma	Light/dark perception	70	Age 50	20
M	Retinopathy of Prematurity	Light/dark perception	31	Birth	31
F	Retinitis Pigmentose	Light/dark perception	37	Birth	37

Table A.2. Blind participant information from experiment 2

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)
M	Retinopathy of prematurity	None	24	Birth	24
F	Leber's congenital amaurosis	Light Perception	43	Birth	43
M	Leber's congenital amaurosis	Light Perception	40	Birth	40
F	Pathological Myopia	Light/dark perception in right eye, Fuzzy colors	57	Age 42	15
F	Retinopathy of Prematurity	None	74	Birth	74
M	Retinitis Pigmentosa	Light/dark perception, some functional peripheral	58	Age 25	23
F	Retinitis Pigmentose	Light/dark perception	63	Age 11	52
F	Retinopathy of Prematurity	Light/dark perception	71	Birth	71

Table A.3. Blind participant information from experiment 3

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)
M	Retinopathy of Prematurity	Light/dark perception	31	Birth	31
M	Retinopathy of Prematurity	Light/dark perception	43	Birth	43
F	Retinitis Pigmentose	Light/dark perception	37	Birth	37
M	Retinopathy of prematurity	None	28	Birth	28

Table A.4. Blind participant information from experiment 4

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)
M	Retinopathy of prematurity	None	24	Birth	24
F	Leber's congenital amaurosis	Light Perception	43	Birth	43
M	Leber's congenital amaurosis	Light Perception	40	Birth	40
F	Pathological Myopia	Light/dark perception in right eye, Fuzzy colors	57	Age 42	15
F	Retinopathy of Prematurity	None	74	Birth	74
M	Retinitis Pigmentosa, atypical, with cone dystrophy	Light/dark perception, some functional peripheral	58	Age 25	23
F	Retinitis Pigmentose	Light/dark perception	63	Age 11	52
F	Retinopathy of Prematurity	Light/dark perception	71	Birth	71

Table A.5. Blind participant information from experiment 5 & 6

BIOGRAPHY OF THE AUTHOR

Hari Prasath Palani was born in Hosur, India on 21th June, 1988. He was raised in Hosur and he graduated from Vijaya Vidyalaya matriculation higher secondary school in 2005. He then attended College of Engineering, Guindy in Chennai, which is one of the four constituent colleges of Anna University, Chennai, India and graduated in 2009 with a Bachelor of Engineering in Geo Informatics. He worked as a Software Engineer in CapGemini Private Limited in India from February 2010 to July 2011. He graduated with a Master of Science degree in the Department of Spatial Information Science and Engineering at The University of Maine in Fall 2013.

In Spring 2014, he started PhD program and extended his masters thesis towards advancement of touchscreen-based graphical access for supporting blind and visually-impaired users. He maintained the position of research assistant and was funded by NSF and NIH. He has given more than 20 talks and poster presentations at national and international conferences. He was awarded the Outstanding Graduate student award for the year 2014. He received 8 awards between 2012-2017 from The University of Maine's Graduate exposition and Research Symposium. He also received two innovation award from Fosters center for student innovation, at the University of Maine. In 2017, he received National Science Foundation's I-Corp grant that supported him to perform in-person interviews across the country with BVI individuals and their broader ecosystem. He is also a reviewer for SIGCHI conference.

Hari Prasath Palani is a candidate for the Doctor of Philosophy in Spatial Informatics from The University of Maine in May 2018.