

Principles for Designing Large-Format Refreshable Haptic Graphics Using Touchscreen Devices: An Evaluation of Nonvisual Panning Methods

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Touchscreen devices, such as smartphones and tablets, represent a modern solution for providing graphical access to people with blindness and visual impairment (BVI). However, a significant problem with these solutions is their limited screen real estate, which necessitates panning or zooming operations for accessing large-format graphical materials such as maps. Non-visual interfaces cannot directly employ traditional panning or zooming techniques due to various perceptual and cognitive limitations (e.g., constraints of the haptic field of view and disorientation due to loss of one's reference point after performing these operations). This article describes the development of four novel non-visual panning methods designed from the onset with consideration of these perceptual and cognitive constraints. Two studies evaluated the usability of these panning methods in comparison with a non-panning control condition. Results demonstrated that the exploration, learning, and subsequent spatial behaviors were similar between panning and non-panning conditions, with one panning mode, based on a two-finger drag technique, revealing the overall best performance. Findings provide compelling evidence that incorporating panning operations on touchscreen devices – the fastest growing computational platform among the BVI demographic – is a viable, low-cost, and immediate solution for providing BVI people with access to a broad range of large-format digital graphical information.

CCS Concepts: • **Human-centered computing** → *HCI design and evaluation methods; Interaction devices;*
• **Social and professional topics** → *Assistive technologies;*

Additional Key Words and Phrases: Accessibility (blind and visually impaired), assistive technology, touchscreens, haptic cues, auditory cues, vibro-audio interface, non-visual maps

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1. INTRODUCTION

Graphical materials represent a key medium of information exchange in educational settings, the workplace, for navigation, or in the myriad of life's everyday activities. Unfortunately, the visual nature of such graphics prevents many people with blindness and visual impairment (BVI) from accessing this wealth of critical information. Non-visual

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access to text-based digital materials has largely been solved through text-to-speech screen reading software such as JAWS (www.freedomscientific.com) and VoiceOver (www.apple.com/accessibility/). However, there are no analogous screen-reading programs for graphical materials, meaning that non-visual graphical access remains a major unmet challenge for millions of BVI individuals. Accessing and interpreting graphical information such as graphs, charts, and maps (commonly referred to as *infographics*) is extremely important as this information is crucial in almost all fields [Smiciklas 2012; Infographics 2015]. *Infographics*, such as maps, form an integral part of navigation, especially in unknown environments. Reading a map can be processed much faster than reading a textual description of the same spatial information as maps are perceptual media, meaning that the spatial relations can be perceived directly from the rendering through the spatial senses of vision or touch. By contrast, text descriptions of the same rendering require cognitive intervention, as language is an interpretive medium [Giudice and Legge 2008]. As a consequence, text-based descriptions of graphics are less precise, more error prone to interpret, and require more cognitive load than a perceptual interface [Temple 1990; Rauterberg 1992; Staggers and Kobus 2000].

Work on tactile maps dates back more than a century, and researchers have devoted considerable effort to their design, development, techniques, and production (For a detailed review on tactile maps and symbols, see Rowell and Ungar, Part 1 [2003] and Rowell and Ungar, Part 2 [2003], and for a web compendium of tactile maps, see Perkins Maps [2015]). Of note, paper-based tactile maps are the most frequently used approach [Eriksson 1998] but they also suffer from several major shortcomings, such as being static, physically large, difficult to author, and require many pages to emboss, especially for maps of large-scale environments. Many of these shortcomings have been addressed through the development of refreshable haptic display. Some notable haptic displays include: Sensable Technologies' PHANTOM devices [Phantom 2015]; tactile pin-based HAPTAC and Virtouch mouse [Hasser 1995; Kammermeier and Schmidt 2002]; camera-based Optacon [Bliss et al. 1970]; Graphic Window Professional (GWP) by Handy Tech [Chouvardas et al. 2005]; the Dots View DV1 by KGS Electronics [Nishi and Fukuda 2006; Kobayashi and Watanabe 2002]; METEC's DMD 12060, Hyperbraille, Hyperflat, and the BrailleDis9000 [Hyperbraille 2015; Völkel et al. 2008; Schweikhardt and Klöper 1984; Pölzer et al. 2016; Kohlmann and Lucke 2015]; There are pros and cons of all of these devices but of note here, they are all single-purpose, non-portable, expensive, and none but the PHANTOM is even commercially available. These limitations have trumped these solutions from reaching the BVI demographic. With the recent advancements in touchscreen-based smart computing devices, several approaches have attempted to provide haptic or auditory access to digital maps. Many studies have demonstrated that use of multimodal cues reduces cognitive load and increases efficacy in learning graphical information [Hoggan et al. 2009; McAdam and Brewster 2011; Williamson et al. 2011; Giudice et al. 2012; Palani et al. 2016; Palani and Giudice 2014]. Most of these smartphone/tablet based solutions utilize the device's built-in vibration motor, but some projects have employed external hardware, such as vibrotactors on the fingers [Goncu and Marriott 2011, 2015], and electrostatic screen overlays, which were coupled with touchscreen devices to generate haptic feedback [Xu et al. 2011; Mullenbach et al. 2014].

While touchscreen-based approaches are promising, they also offer unique challenges due to limitations imposed by haptic perception and the hardware being based on a small, featureless glass surface (as reviewed in Klatzky et al. [2014] and O'Modhain et al. [2015]). Because of these challenges, touch-based non-visual interfaces cannot be developed based on traditional visual guidelines. Some of the perceptual issues related to the nonvisual use of touchscreen displays have been addressed in previous studies

[Giudice et al. 2012; Raja 2011; Palani and Giudice 2014; Goncu and Marriott 2011]. This article addresses the challenges imposed by the limited screen real estate of the underlying device, which still remains as a vexing issue as it constrains the amount of graphical information that can be simultaneously presented. Most maps are large-format graphical materials that are typically larger than the device's display size; and thus, they cannot be accessed in their entirety from a single "view". Visual interfaces overcome this constraint by use of panning and zooming operations. However, non-visual interfaces cannot directly employ these techniques as performing panning or zooming operations with touch is difficult due to both perceptual constraints (e.g., a limited haptic field of view and low haptic resolution) and cognitive constraints (e.g., disorientation due to loss of one's reference point on the map after performing these operations) [Rastogi et al. 2013; Raja 2011; Giudice et al. 2012]. Most existing non-visual graphics access solutions do not require panning or zooming operations as they are based either on hardcopy-tactile or refreshable-haptic displays where the paper or viewing window is fixed. However, when using dynamic touchscreen-based approaches, as is done here, the necessity for panning operations becomes vital owing to the perceptual limitations imposed by the device's featureless glass surface. Studies have shown that graphical elements (i.e., vibrotactile lines) on touchscreen devices should be of at least three times in width compared to hardcopy graphical renderings and should maintain a width of at least $\sim 8.89\text{mm}$ (see Raja [2011]). By contrast, people can visually perceive as small as 0.116mm width of graphical elements at a viewing distance of $\sim 400\text{mm}$ [Curcio et al. 1990]. Because of this huge disparity in spatial perception between encoding modalities, touchscreen-based vibrotactile lines would need to be ~ 77 times wider (i.e., 8.89mm in tactile versus 0.116mm in visual) than that of the visual rendering. This means that most tactile renderings on touchscreen devices will extend beyond the limited display size and will mandate the need for panning or zooming operations. The key goal of this article is to address these challenges by:

- (1) developing novel non-visual panning methods based on consideration of human perceptual and cognitive constraints that are pertinent to the design of surface and touchscreen interfaces, and
- (2) evaluating the usability and efficacy of these panning methods to facilitate accessing, learning, and developing an accurate cognitive representation of digital graphical materials (e.g., maps on touchscreen interfaces).

The remainder of this article is organized as follows: In Section 2, we describe the challenges of implementing the panning operation with touch-based non-visual interfaces by distinguishing it from traditional vision-based panning operations. In Sections 3 and 4, we present the design, method, and results of two human studies that examined the usability and efficacy of performing panning operations using our experimental vibro-audio interface (VAI) prototype. Finally, in Section 5, we highlight some of the advantages, challenges, and ambiguities in accessing digital graphics non-visually using a touchscreen interface. We then discuss the findings from the experiments in terms of early-stage design guidelines and high-level principles that developers should consider when using touchscreen interfaces for nonvisual graphical access.

2. VISUAL PANNING VS. TOUCH-BASED NON-VISUAL PANNING

Panning is a default feature for accessing maps in the vast majority of visual interfaces. Panning operations can be performed using many techniques, such as drag, swipe, tap, and the like. Troublingly, such techniques cannot be used in the same way in non-visual interfaces. In order to better conceptualize this difference, the reader is invited to try to pan a map using their preferred interface (for example, Google maps) with their eyes closed. Assuming no visual access, once panned, the user will likely lose control over

the map, as there is no non-visual orienting reference between the graphical elements perceived before and after panning. Accessing large-format graphical information using panning operations can be conceptualized as a two-step process: (1) panning and bringing the extended graphical material to the current screen view and (2) integrating the graphical elements perceived before and after the panning operation. In a visual context, having a large field of view (FOV) and rapid saccadic eye movements makes it easier for a sighted user to perform the panning operations and simultaneously orient themselves to integrate graphical elements across the panned screens [O'Modhain et al. 2015]. By contrast, touch has a restricted field of view, and tactual exploration is based on a serial process of information extraction [Jones and Lederman 2006]. To conceptualize this better, try looking at graphical elements of a map through a narrow viewing aperture that matches the size of a finger digit and explore it with the intent of comprehending its global spatial structure. With such restricted access, one has to constantly integrate the graphical elements across space and time during their prolonged exploration. Because of this challenging spatiotemporal integration process, comprehension of the global graphical-structure is often slow and inaccurate with touch [Wijntjes et al. 2008; Klatzky et al. 2014]. Given that learning graphical materials with touch by itself is a challenging process and often yields far from accurate results, it is highly likely that incorporation of additional operations such as panning will further increase the cognitive effort of accessing and learning large-format graphical materials [Loomis et al. 1991; Rastogi et al. 2013]. A clear understanding of the perceptual and cognitive differences between visual and tactual exploration is needed to reduce such additional cognitive effort. The following sections will highlight some of the major perceptual and cognitive differences between performing panning operations with vision and with touch.

2.1. Multi-Point vs. One-Point Reference

With vision, one can see and process graphical material as a whole, owing to the large field of view and parallel processing of this modality. This ability facilitates users in referencing spatially separated points on a graphic and simultaneously allows them to integrate graphical information, even while performing the panning operation. Conversely, most of the existing refreshable touch-based displays employ one finger as the primary source of information, and the user has to access this information sequentially. Some displays allow access by whole hand (palm) or multiple fingers [e.g., Völkel et al. 2008], but this accommodation still affords very limited points of contact as compared to vision and often requires additional hardware [Goncu and Marriott 2011]. Because of this limited spatial bandwidth, the graphical information cannot be accessed to its entirety by exploring with fingertip(s) or even through whole hand exploration and thus mandates encoding information through a sequence of touches. This means that the graphical elements should be referenced and integrated across the entire space and time of the exploratory process. Unlike traditional haptic displays, touchscreen-based display cannot utilize multiple fingers or whole hand for exploration. Because of this limitation, accessing finger serve as the only source of reference at any particular time and users must always remember the graphical elements under their finger location. These graphical elements can be utilized as reference points to integrate graphical elements accessed before and after performing panning operations. Many studies have suggested that reference points occur in spatial cognition that provide an organizational structure and are used to define the position of adjacent elements [Sadalla et al. 1980; Sjöström 2002]. Based of this logic, we postulate that maintaining such reference points should be a key design consideration for any non-visual touchscreen based interface. To address this consideration, non-visual panning

techniques should be designed in such a way that the reference point under the finger location remains the same before and after performing the panning operation. This is a primary design requirement for the four panning methods evaluated in this work.

2.2. Supplementary vs. Primary Source

With traditional visual-based panning operations, vision is the primary source for accessing information, and the fingers are utilized only to facilitate the panning behavior by performing gestures such as swiping or dragging. By contrast, with nonvisual touch interfaces, fingers are the primary source for accessing information. Thus, with touch-based interfaces, the perceptual component of information extraction and the physical implementation of the panning operations converge to the same effectors, (i.e., fingers). This limitation rules out the option of incorporating traditional finger-based gesture techniques (such as swipe, drag, or flick) to perform panning operations with touchscreen-based non-visual interfaces. For instance, one could imagine tracing a map with touch, which by itself can be considered a swipe gesture, ruling out the option of using swipe or flick gestures to perform additional operations. To overcome this limitation, novel techniques such as use of multiple fingers or buttons should be incorporated to perform panning operations. To investigate and compare the effectiveness of these different techniques (i.e., multiple fingers, gestures and buttons), we designed our panning methods to incorporate different combinations of these approaches.

2.3. Panning: A Technique, Not a Process

As stated earlier, the sequential-processing nature of tactual exploration makes it difficult for the user to integrate graphical information into a consolidated global structure in memory [Wijntjes et al. 2008]. Corroborating evidence has been found in studies showing that visually-impaired individuals often have particular difficulty organizing and integrating the many elements of tactile maps into a coherent whole [Casey 1978] and that they require more landmarks than their sighted peers to build a global representation in memory [Passini and Proulx 1988]. Sequential learning is often a slow and difficult process; additionally, finger based exploration techniques increase the difficulty in spatio-temporal integration of the graphical elements. Thus, it is of utmost importance to design the panning operation in such a way that it does not further increase the complexity of the learning process or the cognitive effort required to integrate the spatial samples before and after the panning operation. To facilitate this goal, the panning operation should be involved as a part of the sequential exploration process and should not be considered as a separate process by itself. One way to streamline this process is to utilize the existing design constraint of always remembering the finger location (see Section 2.1). That is, the panning technique should be designed such that the user's referenced map location (i.e., their finger location before panning) should remain under their finger location even after performing the panning operation. If this constraint is not possible, the user should at least be notified of where the referenced map location has been moved. The logic here is that the referenced map locations will act as anchor points [Couclelis et al. 1987] and will support the user in integrating graphical elements across the panned screens. Similarly, the panning technique should be easy to remember and apply, so that the user can focus on only learning the graphical information rather than diverting their focus to learning and performing the panning operation. To evaluate this assertion, we incorporated different levels of panning function (i.e., distance and direction of panning) in our four newly designed methods of haptic panning.

3. USER EVALUATION: EXPERIMENT 1

To date, very few researchers have implemented panning operations on non-visual interfaces. Some examples of projects that do exist include a gesture-based panning technique used in an audio-haptic browser for accessing and identifying map elements from a GIS-based web map [Zeng and Weber 2010] and a three-finger-gestural input as used in BrailleDis9000 – a static refreshable display for testing user’s ability to perform panning [Schmidt and Weber 2009]. However, both of these projects focused on the user’s ability to identify graphical elements, understand the gestures, and relate these gestures to panning operations. Neither evaluated the haptic exploration and learning process with respect to the learning of large-format graphical materials and whether the pre-post panned elements were integrated into a global representation in memory, which represents our primary interest in this work. Similarly, several other approaches have also implemented panning. Some notable work include: for scrolling through virtual environments via electronic haptic displays [Magnuson and Rasmus-Grohn 2003; Magnusson et al. 2007]; for accessing drawing area on a KGS’s DV2 braille display [Takagi et al. 2015]; for navigating 3-D topographical surfaces using auditory cues [Walker and Salisbury 2003]; for locating widgets and on the mental model of blind users on the BrailleDis 7200 [Prescher and Weber 2016]; for panning and learning a virtual maps using the Phantom haptic interface and 3D spatialized audio [Schloerb et al. 2010]. These studies investigated the usability of pan functions in achieving a task (e.g., locating a graphical element) but have not investigate the influence of performing panning operations on integrating graphical elements across panned screens and building an accurate mental representation of the information perceived, as are the goals in the current study.

In an earlier study from our lab, the Vibro-Audio Interface (VAI) was used to present large-format maps that extended beyond the device’s screen [Raja 2011]. This work compared learning routes and spatial layouts acquired from learning with: (1) a non-visual equivalent of traditional map panning, called button-based panning, (2) a novel method where the device pans over a fixed virtual map, called device-panning, and (3) a hardcopy tactile map augmented with audio cues [Raja 2011]. Results from this study showed that map learning performance in the two panning conditions was similar to that of the standard hardcopy maps. However, the map learning time with hardcopy maps was significantly faster than the other two conditions. Similarly, *TimbreMap*, a sonification interface, showed that a two-finger based panning technique was efficient for accessing and learning indoor layouts [Su et al. 2010]. Although promising, findings from these studies did not evaluate efficacy and usability of implementing panning operations or address whether their use promotes the development of a global cognitive map. This is mainly because comparisons were made with a hardcopy tactile map, meaning that it is not clear whether the observed similarities/differences in performance were due to innate perceptual differences in the media (i.e., perceiving hardcopy tactile stimuli versus perceiving vibrotactile stimuli rendered on a touch-screen interface). To specifically investigate the influence of the panning operation, it is necessary to ensure that any observed differences are not due to confounding perceptual issues between the mode of access and/or the nature of the panning technique per se. To avoid this perceptual bias, comparisons should be made with the same stimuli and rendering device. Evaluation should be based on similar exploratory, learning, and behavioral tasks compared: (1) between a panning condition and a non-panning control condition, and (2) between different panning techniques.

To our knowledge, no work to date on non-visual interfaces has explicitly addressed the role of panning operations in exploring and learning graphical information, and it remains unclear whether panning operations support or hinder the actual exploration

and learning process. To investigate these issues, two human behavioral experiments were conducted with the following goals:

- (1) to investigate whether users will be able to perform non-visual panning operations of large-format maps that are haptically perceived,
- (2) to assess whether performing panning operations support or hinder the non-visual exploration, learning and simultaneous integration of map elements across multiple pan screens into an accurate cognitive map, and
- (3) to identify whether exploration strategies differ as a function of panning method.

We evaluate these goals by comparing performance on exploration, learning, and several subsequent spatial behaviors between four panning conditions and a fifth non-panning (control) condition. The logic here is that if the exploration, learning, and spatial behaviors are similar between the panning and non-panning conditions, it suggests that users were able to integrate graphical elements across multiple pan screens into an accurate cognitive map. This outcome would also affirm that incorporation of panning operation supports non-visual exploration and learning of graphical materials. By contrast, if the observed performance is found to reliably differ between panning and non-panning conditions, then further investigations must be carried out to address whether the observed differences are due to the panning technique per se or imposed during the non-visual integration process across the different panned screens.

3.1. Method

This experiment extends our earlier approach of using a vibro-audio interface (VAI) on commercial touchscreen devices [Giudice et al. 2012] but does so employing large-format graphics such that the use of panning operations is necessary to access the maps in their entirety. The system works by allowing users to freely explore graphical information on the touchscreen of a commercially available tablet and synchronously triggering vibro-tactile and auditory feedback whenever an on-screen graphical element is touched. Vibrotactile feedback was generated from the device's embedded electromagnetic actuator, i.e., an off-balance motor, which was controlled by Immersion Corporation's embedded haptic player. The vibratory effects for the experimental application were based on the Universal Haptic Layer (UHL) developed by Immersion Corporation (www.immersion.com). A total of 15 sighted participants (8 males and 7 females, ages 19–29) were recruited for this study. All participants gave informed consent and were paid for their participation. The study was approved by the Institutional Review Board (IRB) of the University of Maine and took between 1.5 and 2.5 hours per participant. This study was intended as a proof of concept and as such, inclusion of blindfolded-sighted participants is widely accepted in the preliminary efficacy testing of assistive technology [see Sears and Hanson 2012 for discussion]. Hence, the use of blindfolded-sighted participants is justifiable here as we are testing the ability to access, learn, and represent non-visual material that is equally accessible to both sighted and BVI groups. Adding support for this experimental design decision, our earlier work with the VAI found no differences between blindfolded-sighted and BVI groups [Giudice et al. 2012]. However, we also conducted a follow up study (Experiment 2) with BVI participants as they are the target demographic that will ultimately most benefit from this work.

3.1.1. Experimental Conditions. Five conditions were designed and evaluated. Four of the conditions corresponded to four newly developed panning techniques, and the fifth was a non-panning control condition. We specifically designed four panning techniques for the VAI based on the perceptual factors and cognitive guidelines of touchscreen based non-visual interfaces discussed in Section 3. Each technique represents a specific

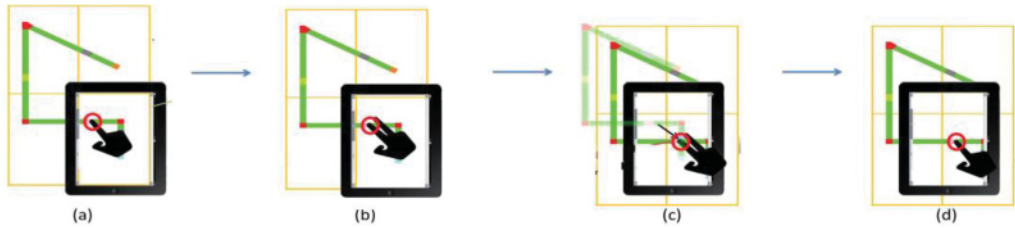


Fig. 1. Two-finger drag panning operation: (a) In explore mode-vibration indicates graphical elements on-screen, (b) pan mode initialized upon placing the additional finger-indicated via clicking sound, (c) map panned by synchronously dragging two fingers-indicated via clicking sound, and (d) removal of second finger-clicking sound stops to indicate that user is back in explore mode.

approach for performing the panning operation and utilizes a unique level of control over the direction, distance, and amount of information being panned.

3.1.2. Two-Finger Drag (TFD) Condition. As the name suggests, this condition utilizes two fingers to perform the panning operation and was inspired by the method used in the *Timbremap project* [Su et al. 2010]. The *Timbremap project* restricted the placement of a second finger to one of the four corners of the screen. However, the authors speculated that this restriction led to confusion while learning, as participants indicated that the largest difficulty they had was using the panning technique. To avoid this confusion, the restriction of “using a second finger in one of the four corners” was replaced in the current design by allowing a second finger to be placed anywhere on the screen. Users could learn the graphical material displayed on a single screen (referred to here as “explore mode”) of the VAI by exploring with one finger. Upon placement of the second finger, panning mode was initiated, and the device notified the user of the mode change via a continuous clicking sound. Once in panning mode, users could pan the graphical material in any direction by dragging it with two fingers synchronously (refer to Figure 1). The panning mode and the clicking sound stopped upon removal of the second finger, indicating to the user that they were back in explore mode. The user’s primary finger was not disturbed during the entire panning process, thereby providing a constant reference of the map location under their finger. We postulated that this fixed reference between the finger and map location should allow the user to continue their exploration after panning with reduced cognitive effort as the reference point remains under their primary finger location.

3.1.3. Button-Touch (BT) Condition. As discussed earlier, work by Raja [2011] suggested that the button-touch technique is an efficient method for non-visual panning. Given the previous results, this panning method was included here to validate its efficacy and to generalize the previous study results to larger and more complex maps. This panning method involves three steps: (1) remembering the existing touch location and raising the primary finger from the touchscreen, (2) pressing the pan button, and (3) placing the primary finger at a different location, such that the last touch-point is now moved so as to be under the newly touched location (refer to Raja [2011] for a detailed description).

3.1.4. Button-Drag (BD) Condition. Both of the previous methods (TFD and BT) represent a unique set of behaviors for accessing the graphical elements. We speculated that some of these behaviors could cause problems while performing the panning operations. For instance, raising the finger in the button-touch pan mode increases cognitive effort, as the user must remember, recall, and confirm their reference map location before and after the panning operation. Similarly, the use of a second finger was occasionally confused with the primary finger, which again increased cognitive load and led to

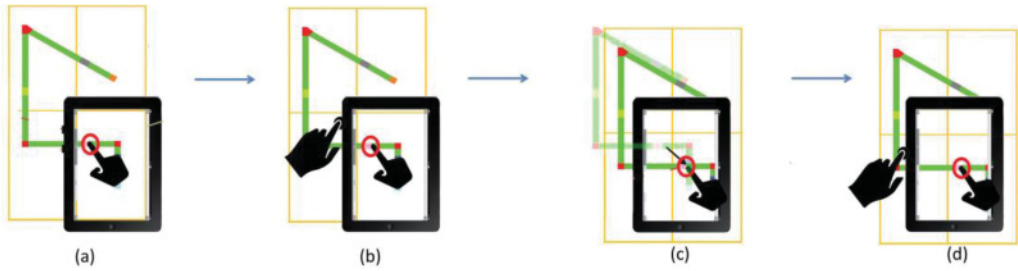


Fig. 2. Button-drag panning operation: (a) In explore mode-vibration indicates graphical elements on-screen, (b) pan mode initialized by pressing the pan start button-indicated via clicking sound, (c) map panned by dragging primary finger on screen-indicated via clicking sound and (d) pressing the pan stop button - clicking sound stops to indicate that user is back in explore mode.

potential confusion for the user (as indicated during pilot studies in the lab with the two-finger drag method implemented on the VAI). Hence, with this button-drag method, pros of the previous two methods were combined; (1) using a button to control the panning mode and (2) using a drag gesture to perform the panning operation.

Unlike the button-touch method, users need not remove their primary finger when using the button-drag method. Pressing the pan-start (volume-up) button initiated the panning mode and was indicated to the user via a continuous clicking sound. Once in panning mode, the user could pan the graphical material in any direction, as needed, by dragging with the primary finger. Pressing the pan-stop (volume-down) button stopped both the pan mode and the clicking sound, thus indicating to the user that they were back in explore mode (refer to Figure 2). This condition was expected to be faster than the previous two, as the primary finger is always in contact with the screen. We also expected a speed accuracy trade-off with this condition. In other words, we postulated that users might not achieve the same level of accuracy in global integration and cognitive map development, as they concentrate less on the reference map location when compared with the two-finger drag and button-touch conditions where the reference location on the map is reinforced by the panning process.

3.1.5. Grid-Tap (GT) Condition. With the above three methods, users could pan the graphical material in any direction and for any distance they desired. However, most of the conventional non-visual panning methods in the literature have restricted these parameters. For instance, in the project “Haptics and Traffic- a pre-study” the panning direction was restricted to either horizontal or vertical movement, and the amount of panning was fixed to a limiting box [Magnuson and Rassmus-Grohn 2003]. This restriction means that users must learn grids of graphical material and integrate the grids in order to visualize the map components as a global spatial image. To investigate the efficiency of such a restricted method, the grid-tap technique was designed here to control panning distance and panning direction. The graphical material was divided into an even number of grids. The size of each grid was matched to the device’s display size such that only one grid could be displayed at a given time. The panning operation moved the grids horizontally or vertically and was initiated by a double-tap gesture. All movements occurred in fixed and predefined increments (i.e., one grid at a time), which matched the device’s screen size. A double-tap gesture performed on the edge of the screen would move the adjacent grid in that direction to the current screen focus (refer to Figure 3). For instance, to view a grid that was to the left of the material currently rendered on the screen, a double-tap gesture would be performed on the left edge of the display. This process is roughly analogous to flipping a page in a book. The device

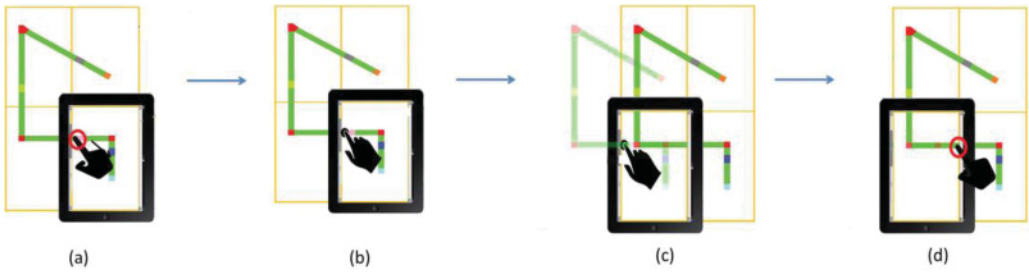


Fig. 3. Gird-Tap panning operation: (a) In explore mode-vibration indicates graphical elements on-screen, (b) Pan mode initialized by double-tap on edge of the screen-indicated via clicking sound, (c) Map panned and adjacent grid comes to view port-indicated via speech output “map panned,” and (d) User back in explore mode.

indicated completion of the panning operation to the user through a speech message, which said “pan done.” Since the grids are all of equal size and the user could integrate them based on direction and adjacency, we expected that this restricted condition would provide a clear reference for alignment and spatial relations between graphical elements.

3.1.6. Non-Panning Control (NPC) Condition. To assess the influence of using panning operations and their subsequent role on spatial and temporal integration of graphical elements, a touchscreen based non-panning condition was included as a control condition. In this condition, the entire graphical content was presented to the user on a single screen using the VAI. The map could be learned in the same way as the other conditions but without performing any panning operations. Since the information content of the underlying graphics remains the same between these five conditions, this control condition was expected to be the fastest and most accurate. As: (1) it avoids the difficulty imposed due to spatio-temporal integration in the other panning conditions and (2) it provides a fixed frame of reference to the entire map as the map was accessed as a unified whole from a single screen.

3.2. Stimuli and Apparatus

The four panning conditions were implemented on a Samsung Galaxy Tab 7.0 Plus tablet, with a 17.78cm (7.0inches with a screen resolution of 170ppi) touchscreen. The control condition was implemented on a similar, but bigger, Samsung Galaxy Tab 10.1 tablet, with a 25.65cm (10.1inches with a screen resolution of 149ppi) touchscreen, allowing presentation of the entire map within the extent of a single screen. The graphical contents were rendered at a line width of 0.35inch on both devices, as this was previously found to be an optimal size for vibro-tactile based learning [Giudice et al. 2012; Raja 2011]. During the experiment, participants sat on an adjustable chair and self-adjusted the seat height such that they could comfortably interact with the experimental devices, which rested on a 76.2cm- (30inch-) high table in front of them. During the learning phase of each experimental trial, participants wore a blindfold (Mindfold Inc., Tucson AZ).

Five indoor corridor layout maps comprised the experimental stimuli (with two additional maps used for practice). Since this is an initial investigation of panning using VAI and its influence in mental modeling, we constrained our evaluation to focus primarily on spatial components of the graphic as opposed to semantic components (e.g., street names on a map). Accordingly, the experimental corridor maps were simplified with more emphasis on the spatial structure. Each map was composed of four corridors, four landmarks, three junctions, and two dead-ends. All maps were designed with a

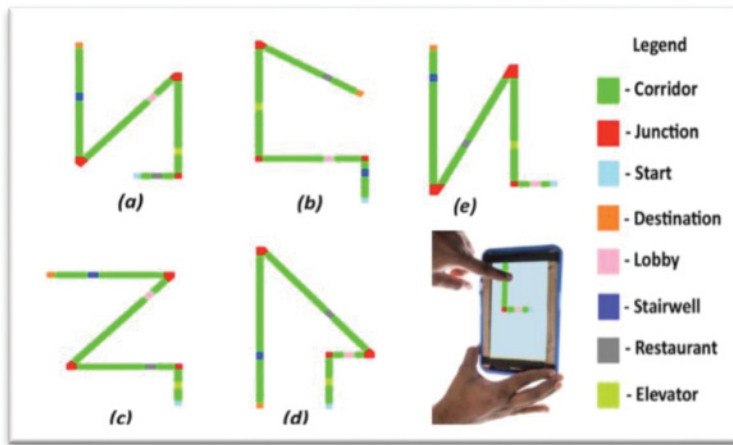


Fig. 4. Experimental stimuli - Corridor layout maps with their landmarks denoted.

frame size that matched an A4-sized paper. The five maps had the same level of complexity but different topology (see Figure 4). The complexity was matched in terms of: (1) number and orientation of corridor segments, (2) number of junctions, (3) number of landmarks and their names: landmarks were named based on a hotel theme and included *Lobby*, *Elevator*, *Restaurant* and *Stairwell*, and (4) position of landmarks: each of the maps had exactly one landmark on each of the corridor segments, and two were always on the start screen such that they could be accessed without any panning operations. Alignment between landmarks is critical in many buildings to support indoor navigation and wayfinding. For instance, the entrance and exit are aligned in many buildings to facilitate navigation. Hence, the three landmarks were positioned in such a way that for each map at least two landmarks were aligned (either horizontally or vertically). The landmarks' positions were purposely designed to assess users' ability to learn and represent their positions in memory. The two dead-ends were the start and destination points, which were provided to the user as a reference during their testing phase. The landmarks, dead-ends and junctions were all indicated to the users via a supplemental audio cue (i.e., a sine tone), and their names were spoken via synthesized speech upon tapping that location.

3.3. Procedure

A within-subjects design was used, with participants running in each of the five conditions. In each condition, participants learned a corridor layout map and performed 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, and a testing phase.

3.3.1. Training Phase. Each of the five conditions began with two training trials, in which the experimenter explained the learning strategies, test measures, their goals, and how to perform the panning technique under investigation. In the first trial, participants explored a practice map with corrective feedback. They were instructed to visualize the corridor layout map as being analogous to a hotel floor layout map with the four landmarks being *lobby*, *elevator*, *restaurant*, and *stairwell* (landmark order was randomized between maps). The experimenter then conducted a mock test-phase to demo the testing tasks. In the second training trial, blindfolded participants were asked to learn an entire map. Practice maps based on a different layout from the



Fig. 5. Pointing device used in the pointing task (left), A4 Canvas for blindfolded-sighted participants' group reconstruction task with start and destination points (right).

experimental map were used in both these training trials. Once the participant indicated completion of learning, the experimenter conducted a mock test-phase. 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. On average, the two practice trials took approximately 15 minutes.

3.3.2. Learning Phase. During the learning phase, participants were first blindfolded and were asked to use the index finger of their dominant hand for exploring and accessing graphical elements. The experimenter then placed participants' primary finger at the start location and instructed them to freely explore the map and try to learn the entire layout. They did not have any restriction on their hand movements but were encouraged to trace the corridor layout from start to end. 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 we wanted to capture the individual differences in learning behavior with respect to the different panning conditions. Once participants indicated that they had completed learning the map, the experimenter removed the device, and participants were allowed to lift their blindfold to continue with the testing phase.

3.3.3. Testing Phase. This phase consisted of two tasks: (1) a pointing task and (2) a map reconstruction task.

In the pointing task, participants indicated the allocentric direction between landmarks using a pointer affixed to a wooden board (see Figure 5). The pointing task consisted of a set of four pointing trials (e.g., indicate the direction from elevator to lobby). The four pointing trials were tied to the experimental stimuli and order was balanced between subjects. Due to time constraints, we did not cover all 10 pairwise combinations of landmark pairs for each stimulus; however, all four landmarks were tested (i.e., either pointed from or pointed to) within the four trials.

In the reconstruction task, participants were asked to draw the map and label the location of the four landmarks on a template canvas of the same size (A4 paper) as the original map. To provide the participants with a reference frame for the map's scale, the start and destination points were indicated on the canvas (see Figure 5).

3.3.4. Feedback Form. Upon completion of all five conditions, participants were asked to fill out a feedback form to capture their opinion about the panning techniques,

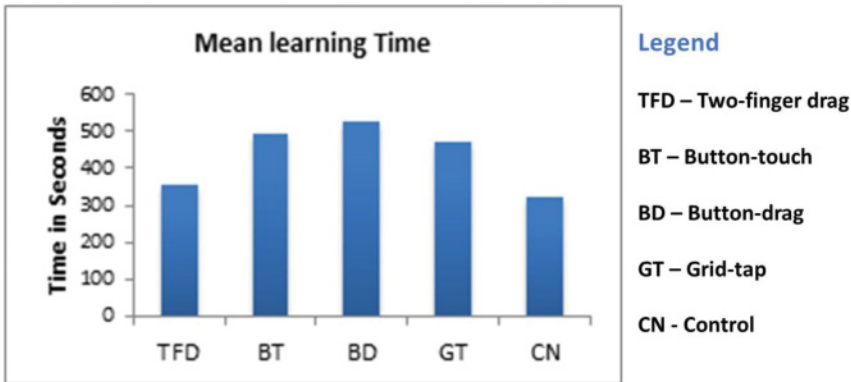


Fig. 6. Mean learning time as a function of pan-mode condition for blindfolded sighted participants.

Table I. Blindfolded-Sighted Group: Mean and Standard Deviation for All Measures as a Function of Pan-Mode

Blindfolded-Sighted group										
Measures	TFD		BT		BD		GT		NPC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Learning Time (in seconds)	354.67	80.20	491.27	198.61	529.20	194.13	472.40	224.56	324.07	99.53
Directional accuracy	17.58	24.97	18.33	20.06	32.67	41.41	29.00	33.96	18.58	25.01
Reconstruction accuracy	0.80	0.41	1.00	0.00	0.87	0.35	0.80	0.41	0.93	0.26
Relative positioning accuracy	0.67	0.49	0.40	0.51	0.67	0.49	0.27	0.46	0.40	0.51
Landmark labeling	3.20	1.01	3.60	0.83	3.47	1.19	3.60	0.83	3.87	0.52
Map traversal iterations	2.00	1.00	2.67	1.29	2.53	1.25	2.67	1.05	3.07	1.28
Subjective rating	2.60	1.05	4.00	0.76	2.80	1.21	3.80	1.36	1.60	0.99

the usability of each, and suggestions for alternative methods. The feedback form also asked the participants to rank order the five pan-mode conditions based on their preference with 1 being the most preferred condition.

3.4. Results and Discussion

From this experimental design, eight measures were evaluated as a function of the five pan-mode conditions, namely: learning time, map traversal iterations, directional accuracy, reconstruction accuracy, relative positioning accuracy, start-screen landmark positioning, landmark labeling accuracy and subjective preference ratings for the five conditions. A set of repeated measures ANOVAs and *post-hoc* paired sample *t*-tests were conducted on each of the measures, based on an alpha of 0.05. The results are as follows.

3.4.1. Learning Time. Learning time was defined as the time taken from the moment a participant touched the screen until they confirmed that they had completed learning the map. The learning time can be interpreted as an indicator of cognitive effort required for internalizing the map as a whole. That is, the greater the learning time, the higher the cognitive load for that condition. The learning time ranged from ~2.5 minutes to ~15 minutes between conditions, with a mean of ~7.5 minutes. Based on ANOVA results, a significant difference in learning time was observed between the five conditions ($F(4,56) = 5.605, p = 0.001$). From the mean learning times (Figure 6 and Tables I and II) and *post-hoc t*-test results, one can infer that the non-panning control condition and the two finger-drag condition were significantly faster than the others,

Table II. Repeated Measures ANOVA Results for Each of the Tested Measures

Measures	Sighted-Participants			
	df		f	Sig.
	Hypothesis	Error		
Learning Time	4	56	5.605	0.001
Times traversed	4	56	3.527	0.012
Relative directional accuracy	4	56	2.232	0.077
Reconstruction accuracy	4	56	1.233	0.307
Relative positioning accuracy	4	56	1.806	0.140
Single screen landmark integration	4	56	0.427	0.788
Landmark labeling	4	56	1.034	0.398
Scale	4	56	8.8	0
Theta	4	56	0.876	0.484
DI	4	56	1.733	0.156

suggesting that these two conditions imposed the least cognitive load on participants and were thus the easiest techniques for extracting the map information during learning. The superior learning time performance of the control condition can be attributed to its fixed frame of reference. Moreover, this condition did not force users to perform any additional operations to perceive the entire map, such as the use of gestures, button presses, or any additional finger actions. However, despite needing to perform an additional panning operation, the learning time of the *two-finger drag* condition was very close to that of the control condition, and there was no reliable difference between these conditions based on the *t*-tests results. This finding supports the efficacy and intuitiveness of the *two-finger drag* technique in promoting the learning process.

3.4.2. Map Traversal Iterations. As described above, all participants were allowed to freely explore and traverse the entire map until they were confident that they had learned the layout. The “map traversal iteration” measure was defined as the frequency of traversals between the start and destination points during exploration before participants deemed they had learned the map. We postulated that lower traversal iterations needed to reach perceived learning indicates a faster map integration process, which is interpreted as representing the intuitiveness and ease of use of the panning technique. As a first step in learning, all participants were asked to traverse the entire map at least once. They were then able to freely traverse back and forth to integrate the map elements to build their own mental map. However, 13 of 15 participants simply explored back and forth along the path from start to destination. Only two people employed an off-route strategy to identify the alignment between landmarks, which was not considered as a traversal iteration. Based on the log files, only a complete traverse between the start and destination with three junction points was considered as a traversal iteration. The means for each of the conditions are given in Table I. The number of traversal iterations significantly differed between conditions ($F(4,56) = 3.527$, $p = 0.012$). The data (see Tables I and II) shows that participants made fewer traversals in the *two-finger drag* condition. This was also evident from post hoc paired sample *t*-tests, which showed a significant difference (all $p_s < 0.05$) between the *two-finger drag* and the other conditions. The control condition was also significantly different from the *two-finger drag* condition. However, the higher number of traversals for the control condition could be attributed to the fact that the entire content was accessible within the single display screen, making it easier to traverse back and forth. We interpret the fewer traversal iterations used in the *two-finger drag* method as indicating that this technique is the most intuitive and easiest to use panning method of the four methods tested.

3.4.3. Directional Accuracy. Directional accuracy was defined as the accuracy in performing allocentric pointing judgments between landmarks. Absolute angular errors were measured by comparing the angles reproduced by the participants with the actual angles between the landmarks. Results based on a paired sample *t*-tests suggested a strong trend in directional accuracy between the five pan-mode conditions. By comparing the means of the directional errors (refer to Table I), one can infer that the participants were more accurate in indicating relative directions with the *two-finger drag*, *control*, and *button-touch* conditions as compared to the *button-drag* and *grid-tap* conditions. This inference was confirmed by the post-hoc paired sample *t*-tests, which showed that performance in the *button-drag* and *grid-tap* conditions exhibited significantly more errors than the other three conditions, which did not differ reliably from each other. Better accuracy with the non-pan *control condition* was expected, as it provides a fixed frame of reference between the landmarks. Interestingly, the *two-finger drag* and *button-touch* were equally accurate even without a fixed frame of reference. This outcome suggests that participants were able to visualize the map in its entirety and perform accurate spatial behavior by accessing their global cognitive map, as the pointing direction is not measured along traveled paths and requires use of spatial inference to make accurate straight-line pointing judgments.

3.4.4. Reconstruction Accuracy. This term is defined as the participant's accuracy in physically reconstructing the vibro-audio rendered map. Accuracy was measured by comparing the reconstructed map against the actual map. The reconstructed maps were analyzed using bi-dimensional regression [Tobler 1994]. For this analysis, seven anchor points were selected from each of the maps (i.e., three junctions 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 determines how much and in which direction the reconstructed map was rotated with respect to the actual map. The Distortion Index represents a standardized measure of the overall difference between the reconstructed map and original map, taking into account both scale and rotation [Tobler 1994; Friedman and Kohler 2003]. Results suggested that there were no significant differences for either theta or the distortion index (all *ps* >0.05). This finding suggests that participants had built up and were accessing accurate cognitive maps for all of the panning methods tested. However, there was a significant difference between conditions observed for the scale factor of the reconstructed maps ($F(4,56) = 8.8$, $p < 0.001$). This finding suggests that the ensuing cognitive map was perceived to be of different sizes in different conditions. This difference in scale perception could be due to the interaction technique required for each of the pan-mode conditions, as they all involved a different magnitude of panning distance and direction. *Post-hoc* paired sample *t*-tests showed that the *two-finger drag* condition did not reliably differ from the *control* condition ($t(14) = -1.395$, $p = 0.185$), but was significantly different from the other three conditions (all *ps* <0.05). This finding provides further evidence supporting the efficacy of the *two-finger drag* method and demonstrate that it is not only intuitive but also supports development of an accurate cognitive representation of large-format maps.

3.4.5. Relative Positioning Accuracy. As discussed in Section 3.2, each map had at least two landmarks that were aligned (either horizontally or vertically). Understanding such spatial relations is a crucial component for grasping the global structure of any map. Hence, the reconstructed maps were analyzed for the positional accuracy between the two originally aligned landmarks. Discrete scoring was applied based on the accuracy in alignment of the landmarks (i.e., 1 if aligned within 5 degrees, 0

otherwise). ANOVA and *post-hoc* paired sample t-tests showed no statistically significant differences between the five conditions (all $p_s > 0.05$). However, there was a significant difference between accuracy in vertical and horizontal alignment ($F(1,35) = 15.102, p < 0.01$), with vertically aligned landmarks being more accurate than horizontally aligned landmarks for all five conditions. The cause of this difference may be due to the fact that the vertical frame of the device is nearly twice the size of the horizontal frame (i.e., 6.02 inch vertical versus 3.5 inch horizontal). This allowed participants to compare the vertically aligned landmarks within a single screen extent and easily relate them to each other.

3.4.6. Landmark Labeling Accuracy. Labels are a crucial piece of the qualitative information of maps, as forgetting or swapping the labels might ultimately change the map represented. Discrete scoring was applied based on the correctness of the landmark labeling (i.e., 0 if none were correct and 4 if all four were correct), which was measured from the reconstructed maps. Similar to relative positioning and start-screen landmark positioning, results revealed no significant difference between conditions (all $p_s > 0.05$). Taken together, the results of these three measures provide additional evidence for the hypothesis that performing panning operations does not interfere with the actual learning process. Furthermore, numerical values of these measures suggest that panning conditions were actually more accurate than the non-panning control condition. Albeit not statistically reliable, the null results are important as they suggest that including panning operations did not impair the learning process, and may have even been beneficial, by reinforcing the landmarks and enhancing their cognitive representation in the map.

3.4.7. Start-Screen Landmarks vs. Panned-Screen Landmarks. As discussed in Section 3.3, the start-screen of each condition always contained two landmarks, which could be accessed without performing panning. We expected that the accuracy in positioning and labeling of these two landmarks would be more accurate than that of the two landmarks from panned-screens, which can only be accessed after performing panning. Also the difference in accuracy should be consistent across all four panning conditions, as there were no differences between any of the conditions in the manner the start screen was accessed. However, the fact that participants performed different panning techniques to trace back and forth between the start and destination could alter the cognitive representation of the start screen. To investigate this possibility, the positioning and labeling accuracy of the start screen landmarks was compared with the panned-screen landmarks. Correctness of the landmark positioning was measured from the reconstructed maps by overlaying them over the actual experimental maps. A reconstructed landmark position was considered correct if it fell within the tolerance distance (± 5 cm) from the actual position of the landmark. Discrete scoring was applied based on the correctness of the landmark positions (i.e., 2 if both landmarks were positioned correctly, 1 if only one landmark overlapped correctly, or 0 if there was no overlap). Similar to the relative positioning accuracy, results showed no significant differences between the combined accuracy of the start screen landmarks and combined accuracy of the panned-screen landmarks (all $p_s > 0.05$). The lack of significance was also consistent across the five different pan-mode conditions. This finding demonstrates that the non-visual integration process did not introduce an undue cognitive burden on the ensuing mental representation, as the positioning and labeling accuracy of the two landmarks accessed via panning did not reliably differ from the start screen landmarks.

3.4.8. Subjective Rating. Participants were asked to order the panning methods based on their preference (with 1 being the most preferred). The orders were then analyzed to evaluate each user's preference for the panning techniques. Preference order suggested that participants clearly preferred the non-panning (control) condition (mean = 1.6).

Table III. Blind Participant Information from Experiment 2. M = Male, F = Female

Sex	Etiology of Blindness	Residual Vision	Age	Onset	Years (stable)	Mobile Device Usage
M	Posterior polymorphis dystrophy	Light Perception	18	Birth	18	iPhone/iOS
F	Stargartz	Light Perception	20	Birth	20	N/A
F	Retinitis pigmentosa	Light Perception	22	Age 16	6	iPhone/iOS
M	Leber's congenital amaurosis	Light Perception	24	Birth	24	iPhone/iOS
F	Leber's congenital amaurosis	Light Perception	43	Birth	43	iPhone/iOS
M	Leber's congenital amaurosis	Light Perception	40	Birth	40	iPhone/iOS

This makes sense, as this method did not require participants to perform any additional operations of the map in order to perceive its entire extent. Of the four panning conditions, the two-finger drag condition stood out as the most preferred (mean = 2.6) followed by the button-drag condition (mean = 2.8). The subjective preference along with the performance on all other tested measures suggest that, given a choice, participants preferred panning using the two-finger drag technique or button-drag technique.

4. EXPERIMENT 2

Our primary focus in Experiment 1 was to investigate whether users can learn and represent large-format graphical materials using panning operations with touch. However, it is important to investigate our approach among people with blindness and visually impairment (BVI) as they are the intended target demographic of this technology and the primary users of accessible maps. Although sighted participants are less accustomed to using haptic cues as a primary mode of information gathering, earlier studies with auditory graphs [Walker and Mauney 2010] and tactile maps [Giudice et al. 2011] found no differences between blind and blindfolded-sighted participants, suggesting equality in spatial and geometric information accessibility. Furthermore, graphical material such as graphs and maps are primarily composed of spatial and geometric elements. These elements are equally accessible to both BVI and sighted people, as these features can be apprehended purely through nonvisual means. To add support to this argument and to corroborate the validity of the outcomes found in Experiment 1, a second experiment was conducted with blind participants.

A total of six blind participants (three males and three females, ages 18–43, see Table III for Blindness information) were recruited for this study. All gave informed consent and were paid for their participation. The study was approved by the Institutional Review Board (IRB) of the University of Maine and took between 1.5 and 2.5 hours per participant. This experiment was primarily carried out as a usability study for the targeted BVI demographic. As such, incorporating six subjects is a reasonable sample size here as the literature suggests that five/six subjects are sufficient for assessing usability and identifying the vast majority of problems with the interface [Shneiderman et al. 2009]. The purpose of this experiment was twofold: (1) to validate the outcomes of Experiment 1 with data from the target BVI demographic, and (2) to assess the usability of the panning techniques and interface with this demographic. All the methods, procedure, stimuli, and apparatus were the same as were used in Experiment 1. The only procedural difference was that the reconstruction task was done on an A4 canvas with pins and ribbon (see Figure 7). The start and destination points were depicted with pins prior to the testing phase, and participants were asked to reconstruct the map using pins and a ribbon (i.e., ribbon representing the corridors and pins representing the junctions and landmarks).

4.1. Results and Discussion

Similar to Experiment 1, eight measures (i.e., *learning time*, *map traversal iteration*, *directional accuracy*, *reconstruction accuracy*, *relative positioning accuracy*, *start screen*



Fig. 7. Reconstructed map with ribbon and marking pins (landmarks and junctions) on an A4 Canvas.

Table IV. BVI Group: Mean and Standard Deviation for All Measures as a Function of Pan-Mode

BVI Group										
Measures	TFD		BT		BD		GT		NPC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Learning Time (in seconds)	477.41	225.88	409.0	166.37	413.33	190.23	492.5	178.36	239.00	60.08
Directional accuracy	15.83	17.42	15.63	15.20	9.79	13.31	25.42	20.58	20.83	36.23
Reconstruction accuracy	1.00	0.00	0.66	0.50	1.00	0.00	1.00	0.00	0.83	0.41
Relative positioning accuracy	0.50	0.55	0.50	0.55	0.66	0.52	0.83	0.41	0.50	0.55
Start screen landmark integration	0.83	0.41	0.50	0.55	0.33	0.52	0.50	0.55	0.33	0.52
Landmark labeling	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00	4.00	0.00
Map traversal iterations	1.67	0.82	2.00	0.89	1.83	0.75	2.33	1.03	2.17	0.75
Subjective rating	2.00	0.89	3.17	1.33	3.17	1.33	4.17	0.75	2.50	1.97

landmark positioning, landmark labeling, and subjective ratings) were evaluated as a function of the five pan-mode conditions (see Table IV for mean and SD). A set of repeated measures ANOVAs and related *post-hoc* paired sample *t*-tests were conducted on each of the measures with an alpha of 0.05. In contrast to Experiment 1, neither ANOVA results (see Table V) nor subsequent *post-hoc* paired sample *t*-tests revealed any significant differences between the five conditions for any of the eight measures tested (all $p_s > 0.05$). Only the learning time between non-panning control condition and button-drag was significantly different based on paired sample *t*-test ($T(5) = 2.829$, $p = 0.037$).

As with Experiment 1, the most important outcome of this experiment was the finding that performance with all measures (except learning time) was similar between the panning conditions and the no-pan control condition. It is important to note that this similarity is not due to either a ceiling or floor effect as the error/accuracy performance (Table IV) was in line with results from empirical studies that employed similar learning and testing tasks [Giudice et al. 2011; Waller et al. 2002]. Together, these findings add support and corroborate the results from Experiment 1, which showed that incorporation of panning operations did not hinder the learning process or the mental representation of the perceived graphical material. A repeated measures between-groups ANOVA (blind and visually-impaired group versus blindfolded-sighted) with the conditions as random factors suggested no significant differences (all $p_s > 0.05$) between the participant groups for all measures except map traversal iterations, start screen landmark positioning, and landmark labeling, where the BVI group showed advantages. From the means and SD of traversal iterations, it can be inferred that the

Table V. BVI Group: Repeated Measures ANOVA Results for Each of the Tested Measures

ANOVA - BVI Group				
Measures	df		f	Sig.
	<i>Hypothesis</i>	<i>Error</i>		
Learning Time	4	20	1.998	0.134
Times traversed	4	20	0.954	0.454
Relative directional accuracy	4	20	1.21	0.338
Reconstruction accuracy	4	20	1.818	0.165
Relative positioning accuracy	4	20	0.69	0.608
Start screen landmark positioning	4	20	0.926	0.469
Scale	4	20	0.075	0.989
Theta	4	20	0.26	0.9
DI	4	20	0.518	0.724

BVI group was faster than blindfolded-sighted participants, with significantly fewer iterations ($F(1,4) = 28.007$, $p < 0.006$). Similarly, the BVI group was more accurate in the labeling task compared to the blindfolded group ($F(1,4) = 17.515$, $p < 0.014$). This faster and more accurate performance of the BVI group can be attributed to the fact that these participants had implicit knowledge and more general experience with haptic learning. Despite this small advantage, overall behavioral performance was remarkably similar between the two participant groups, which validates the use of blindfolded-sighted participants as a representative sample in conjunction with BVI participants in usability studies. Our findings also provide corroborating evidence with other studies in the literature showing that the ability to learn, integrate, and represent graphical information is similar between sighted and blind participants [Giudice et al. 2011, 2012]. Unlike Experiment 1, where the two-finger drag and button-touch method stood out as the most preferred panning techniques showing overall better performance, none of the five conditions showed any reliable performance differentiation in Experiment 2. However, similar to the blindfolded group, BVI participants also expressed a higher preference for the two-finger drag method.

5. GENERAL DISCUSSION AND FUTURE WORK

This article addressed the challenge of presenting non-visual access to large-format graphical materials on touchscreen-based interfaces via development and evaluation of four novel non-visual panning methods. Two studies investigated usability of the panning methods and their influence on map exploration, learning, and subsequent spatial behaviors based on development of an accurate cognitive representation of the perceived maps. Although there were differences between the panning and non-panning control conditions in the time needed to learn the maps (see Figure 8), overall results from the eight tested measures with two participant groups demonstrated that the exploration, learning, and performance on subsequent spatial behaviors were remarkably similar between panning and non-panning conditions. Each of the eight measures tested requires accessing of an accurate cognitive map to perform spatial inference and behavioral tasks. For instance, the variables involving pointing between landmarks and map reconstruction require knowledge of non-route Euclidean information that is only possible if participants developed an accurate cognitive map to infer these spatial relations. The error performance across the tested measures provides clear evidence that implementing panning operations on non-visual interfaces does not impose any detrimental effects, but indeed supports the exploration, learning, and building of an accurate cognitive map. Corroborating the trend from the two experiments, it can be inferred that large-format graphical material can be learned

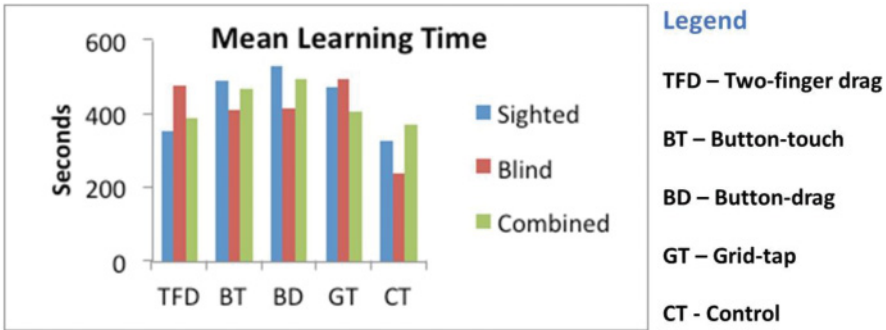


Fig. 8. Mean learning time as a function of pan-mode for blindfolded-sighted group, blind group and combined.

using non-visual means and that panning does not negatively impact the learning and cognitive mapping process. Of the four panning approaches tested, the two-finger drag technique revealed the best map learning performance and was also the most preferred method based on user ratings.

The findings of these studies are a useful first step towards providing guidance for developing refreshable, nonvisual interfaces for conveying large-format graphics on limited-information displays such as smartphones and tablets. As discussed in Section 3, the need for panning operations is vital in touchscreen interfaces due to the restricted field of view and limited resolution of touch, and the device's limited screen real estate. It is worth noting that the observed errors in the panning conditions were not due to the panning operation per se, as they were similar for both panning and non-panning conditions. Interestingly, for all the tested measures, except learning time, performance with at least one of the panning conditions was numerically better than the control condition. For instance, in Experiment 1, learning time with the *Two-Finger Drag (TFD)* method was almost equivalent to that of the non-panning control condition and performance in other measures were numerically better than the control. This finding could be attributed to the fact that participants had to put more cognitive resources to remember their finger location before and after panning, which may have reinforced the location in memory while learning. This suggests that such involuntary reinforcement while panning would strengthen the spatiotemporal integration of the graphical elements across different pan screens and enhance non-visual learning. While all four panning conditions were similar across most measures, the overall results suggest that performance with the *two-finger drag condition* was better than the other three conditions. This was evident from the superior performance on learning time and reconstruction tasks observed for this condition. Similarly, accuracy in the pointing tasks was better with the button-drag condition than the other panning conditions. In addition, subjective preferences from both participant groups showed that, given the choice, participants preferred to use the *two-finger drag* technique.

These findings add support for our design considerations (discussed in Section 3) of (1) Always maintaining a reference location under the user's primary finger, (2) Using multiple fingers or buttons to supplement the panning operations, and (3) Having a simple panning technique as opposed to the technique being a process in itself. While all four panning techniques adhere to these three considerations, each technique was implemented in a unique way, which notably influenced user performance and preference. The two methods (i.e., *two-finger drag* and *button-drag*) where users' primary finger was always in contact with the graphical elements, exhibited better performance and received higher preference ratings than the other two panning methods

(i.e., *button-touch* and *grid-tap*), where the primary finger must be lifted and placed elsewhere on the display after panning. As discussed earlier in Sections 2.2 and 2.3, it is important to ensure such finger contact and gestural interactions whenever possible to smoothen the non-visual learning process. In both experiments, participants had difficulty in tracing and following slanting lines (i.e., lines that are not perpendicular with respect to the device's frame of reference). In the post-study feedback form, many participants reported that staying oriented when tracing slanting lines was one of the hardest tasks during exploration. Future work should acknowledge this challenge and provide supplementing audio, speech or vibrotactile feedback to facilitate better perception of curved and non-rectilinear stimuli.

When designing an effective non-visual touchscreen interface employing panning operations or zooming operations (as implemented in Palani et al. [2016]), it is important to consider the following advantages, challenges and behavioral ambiguities that were observed across both the experiments. It is worth noting that these are not meant as a formal set of design guidelines for developing vibrotactile stimuli for use on touchscreen interfaces such as the VAI. Instead, they should be considered as a starting point for deriving guidelines that will drive this new form of non-visual information access technology.

- (1) *Panning Techniques*: Irrespective of the panning technique, results demonstrated that integrating information with panning is not only possible but also leads to accurate mental representations and behaviors that are functionally equivalent to the mental representations and behaviors observed from the non-panning control condition. While all four techniques proved to be efficient in achieving the task, each technique has its own pros and cons. Understanding such pros and cons is necessary for future implementation. For instance, the *two-finger drag* technique can be implemented for tasks that require quick exploration as this method was found to be the most accurate, fastest to perform, and to require the least cognitive load in learning the map. Similarly, the grid-based pan function might be implemented for tasks that do not require quick exploration but instead demand concentration on alignment between graphical elements.
- (2) *Preference vs. Performance*: Results showed that there was no correlation between the participants' preference for a particular panning technique and their ability to accurately learn the map using that technique. For instance, in Experiment 1, participants mostly preferred the control condition, but their overall performance was better when using the *Two-Finger Drag* (TFD) method. Even when only comparing between the four panning conditions, the *button-touch* method was one of the least preferred methods but its performance in reconstruction, directional accuracy, relative positioning, landmark labeling and single-screen landmark positioning were numerically better than *button-drag* and *grid-tap*. This demonstrates that there is a trade-off between preference and performance, which should be considered and implemented accordingly.
- (3) *Orientation of the Device*: Results showed that participants were able to recall alignment more accurately when the landmarks were vertically aligned. We suggested that this was due to the aspect ratio (128:75) of the device. This allowed participants to bring both landmarks into a single viewport and relate them easily when in portrait view. Future designs should consider the device's aspect ratio and orientation, and utilize the screen real estate to maximize accessibility between graphical elements.
- (4) *Extending the Bounds*: In a pilot study, we found that during the panning process the map could possibly be dragged out of its boundary when panned beyond its extent. With standard visual interfaces, the map automatically resumes to fit the

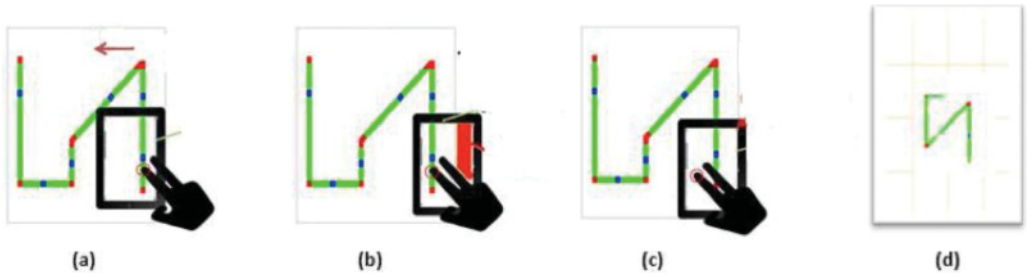


Fig. 9. Map resume concept: (a) Map position before panning, (b) empty space created when panned beyond the screen extent, (c) map resumes automatically filling the empty space and (d) experimental stimuli with white space matching screen size on all sides.

screen extent in such scenarios (refer to Figure 9). However, for touch-based non-visual interfaces this change in map position should be indicated to the user via additional feedback. Even if the users were alerted to the automatic adjustment of map extent, the change in position could confuse the users and force them to lose their reference finger position within the screen space. To avoid this confusion, sufficient white space was included around the actual map extent such that the map would extend beyond the screen when it was pulled out of its bounds (refer to Figure 9). Future implementations of non-visual touchscreen interfaces should consider this in their design and provide supplementing audio or tactile cues to indicate this change to the user.

- (5) *Repositioning the Map*: Users can easily lose their orientation or forget where they are while exploring maps using non-visual techniques. Corrective action requires them to get back to a known point or the start position in order to regain their orientation on the map. In an earlier study with the VAI, a technique was implemented to facilitate re-positioning of the map when users became disoriented or forgot their position within the map [Raja 2011]. Although this was not a part of the current design, by analyzing finger traces and user feedback, we found that participants did indeed experience difficulty getting back to a known location when they became disoriented or lost within the map. This problem could be resolved by adding additional functionality to assist the user with “snapping back” to the start position or any other known location.

In conclusion, this study set out to contribute to the development of multimodal information access technology for providing nonvisual access to large-format graphics. In our information-driven culture, graphical information is a major component that blind and visually impaired users have largely been denied access to. Gaining access to graphical material could have a huge impact on more than 285 million visually impaired people in their educational, vocational, and social settings [World Health Organization 2011]. Touchscreen devices comprise the fastest growing computing platform among people with blindness and visually impairment, owing to their multitude of accessible apps and built-in universal design features [Bilton 2013; Giudice et al. 2012]. It is hard to know the exact number of visually impaired users with smartphones, but informal surveys among people with blindness who have participated in studies in our lab and the many BVI people we interact with professionally and through social/advocacy organizations, leads us to estimate that 70–80% of BVI people who use a cell phone are using a smartphone [Palani et al. 2016]. Thus, building accessible interfaces using such devices is timely and makes good sense. This article provides compelling evidence that touchscreen-based multimodal interfaces (such as the VAI studied here) are a viable and immediate solution for solving the long-standing graphical accessibility gap.

The reality is that panning operations must be incorporated on such interfaces, because without this functionality, accessing large-format graphics non-visually would not be possible. To date, commercial touch-based navigation systems have only used static graphical materials but the current results suggest that future development of this technology should consider inclusion of panning operations to support dynamic graphical access for accurate map learning and cognitive map development. Finally, performance across multiple measures, representing several underlying spatial abilities, as well as informative post-test subjective preferences, provide important end-user input about the efficacy and utility of the two-finger drag and button-drag methods evaluated here for performing non-visual panning operations. Future touchscreen-based multimodal interfaces should consider incorporating panning methods such as the *two-finger drag* and *button-touch* techniques to provide BVI people with dynamic graphical access.

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