A STUDY TOWARDS DEVELOPMENT OF AN AUTOMATED HAPTIC USER INTERFACE (AHUI) FOR INDIVIDUALS WHO ARE BLIND OR VISUALLY IMPAIRED

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A STUDY TOWARDS DEVELOPMENT OF AN AUTOMATED HAPTIC USER INTERFACE (AHUI) FOR INDIVIDUALS WHO ARE BLIND OR VISUALLY IMPAIRED

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Virginia Commonwealth University.

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Acknowledgement

I want to thank my mentor and adviser, Dr. Dianne T.V. Pawluk, without whom I would not have been able to be where I am. Thank you for your guidance and support in my research. I would also like to thank Mrs. Janice Johnson and Dr. Jessica McKinney-Ketchum for sharing their expertise and my PhD committee members for their time, support and guidance.

To want to thank my wife Mrs. Jennette Mateo Rastogi, for being by my side throughout this journey of my graduate student life and for bringing out the best in me and for encouraging me during tough times. To my parents Mr. UmaShanker Rastogi and Mrs. Geeta Rastogi, thank you for the unfailing love to build up my personality, for the support and encouragement to make important decisions in my life. I want to thank you for believing in me and making it possible for me to come to United States to pursue higher education. To my sister, Ms. Gunjan Rastogi and my nephew Utkarsh Rastogi thanks for all the inspiration.

I would like to thank all my labmates, David Burch, Ketan Vidwans, Patrick Headley, Victoria Hribar and all participants of the study for all their support. I am also especially thankful to all my friends in VCU, especially Ms. Sharon Lewis, thank you for all the support and prayers for my overall personality development. Above all, I would like to thank God, for continuous provision and steering. Without Him, I am nothing.
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Abstract

A STUDY TOWARDS DEVELOPMENT OF AN AUTOMATED HAPTIC USER INTERFACE FOR INDIVIDUALS WHO ARE BLIND OR VISUALLY IMPAIRED

By Ravi Rastogi, MS

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Virginia Commonwealth University.

Virginia Commonwealth University, 2012

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An increasing amount of information content used in schools, work and everyday living is being presented in graphical form, creating accessibility challenges for individuals who are blind or visually impaired, especially in dynamic environments, such as over the internet. Refreshable haptic displays that can interact with computers can be used to access such information tactually. Main focus of this study was the development of specialized computer applications allowing users to actively compensate for the inherent issues of haptics when exploring visual diagrams as compared to vision, which we hypothesized,
would improve the usability of such devices. An intuitive zooming algorithm capable of automatically detecting significant different zoom levels, providing auditory feedback, preventing cropping of information and preventing zooming in on areas where no features were present was developed to compensate for the lower spatial resolution of haptics and was found to significantly improve the performance of the participants. Another application allowing the users to perform dynamic simplifications on the diagram to compensate for the serial based nature of processing 2D geometric information was tested and found to significantly improve the performance of the participants. For both applications participants liked the user interface and found it more usable, as expected. In addition, in this study we investigated methods that can be used to effectively present different visual features as well as overlaying features present in the visual diagrams. Three methods using several combinations of tactile and auditory modalities were tested. We found that the performance significantly improves when using the overlapping method using different modalities. For tactile only methods developed for deaf blind individuals, the toggle method was surprisingly preferred as compared to the overlapping method.
INTRODUCTION

Visual diagrams play an important role in the learning and understanding process of unfamiliar information (Hasty, 2009). For one, a simple glance of a visual picture can provide much more information than several lines of text. Second, some aspects of pictures, such as spatial information, can be difficult to put into words. As a result, a growing amount of graphical information is being presented in visual form (Hasty 2009). This widespread use of visual diagrams can be seen across individuals of all ages, starting as early as teaching infant some of their first words to later in life for understanding complex information in science, mathematics, geography and so on. Unfortunately, something that is so revolutionary in the learning and understanding process of sighted individuals has severely limited the independent access to this information for the 3.4 million individuals who are blind or visually impaired (Center for Disease Control and Prevention, 2011) in Unites States alone. Further to consider is that diagrams are not just restricted to physical forms but, with the introduction of multimedia in our daily lives, much of this information is now being presented or is available through some form of digital media, such as over the internet. Access to visual diagrams in these dynamic
environments is becoming a growing concern for people who are blind or visually impaired (Iglesias et al., 2004; Way & Barner 1997).

Individuals who have lost vision rely heavily on other senses, such as touch and hearing, either alone or in combination to assist them in accessing visual information. Several different methods and techniques have been developed and are frequently being used (Power & Jurgensen, 2010) to provide access to visual information depending on the need and visual impairments of the individuals. Several examples are: tactile diagrams, text to speech applications (JAWS), force feedback displays, multi contact refreshable haptic displays and so on. However, there is still a dire need for assistive technology that is automated, easy to use and universal (avoiding multiple devices) for providing access to visual diagrams. The problem that we will focus on in this work is that these diagrams can be very difficult to interpret when presented in alternate form, such as through haptics. We will discuss and present a novel computer tool that was designed to solve the inherent problems with haptic processing when exploring visual diagrams, in a manner that is natural, intuitive and convenient to use by individuals with visual disabilities.

Currently there are many different methods that are being used to supplement or replace visual diagrams, based on need and diagram complexity. One such method that is very frequently considered is **word descriptions**. These word descriptions are typically provided in one of two forms, either in Braille or orally, depending on the situation or preference of the individuals. Using Braille, this information is presented to a user in either physical form or electronically using refreshable Braille displays (4x2 dots per cell). Providing information orally is mostly done either by a sighted person explaining the
diagram to the user or by using screen reading software’s such as Jaws (Freedom Scientific Inc., 2011) or other text to speech (TTS) applications.. Even though this method is convenient, word descriptions are very inadequate in explaining unknown spatial information on visual diagrams (e.g., Figure 1), such as building layouts, patterns in diagrams, scale relationships in diagrams and so on. This likely result in a poor understanding of the information as compared to individuals with vision. Secondly, word descriptions might not always be present with visual diagrams. Thirdly, by relying on others to interpret the diagram this hinders independent discovery of relationships between elements. This is worst for growing children as it might hamper independent learning, essential for the overall development.

Figure 1: Complex geographic map of mean annual rainfall distribution. *Retrieved from http://www.britannica.com/EBchecked/media/50330/Global-distribution-of-mean-annual-rainfall
Another alternative that is frequently considered to improve independent access and understanding of visual diagrams is **tactile diagrams** (Edman, 1992; Hasty, 2009; Hasty, 2010; Loomis & Lederman, 1986). These diagrams are the tactile equivalent of visual diagrams. Typically, tactile diagrams consist of raised patterns or edges on a flat background, which can be felt tactually on the fingers of the users when exploring the diagram (Figure 2). The spatial layout of the information on the diagram is obtained by touching and following the raised edges using a single or two hands to make a mental picture. There are three main types of tactile diagrams, thermoform, raised line drawings and textured diagrams, which are commonly used. These can either be presented alone or in combination with word descriptions for a better understanding of the spatial layout of the information being explored tactually.

Although it is argued that the process of creating tactile diagrams is fast and cheap, it is mostly true for diagrams that are very commonly used or produced on large scale. For visual diagrams that may be used once by one person, the typical process of creating a tactile equivalent is usually time consuming, expensive and requires some form of experience. Additionally, for the production of these diagrams, specialized machines or textured materials (e.g., fabric, fabric paints, and so forth) are needed (Edman, 1992; Braille authority of North America, 2010; Creative common licenses, 2011) and the resulting diagrams are, in general, very bulky to carry around. Their physical nature also limits their use in dynamic environments, such as in exploratory data analysis, where individuals might create many diagrams that they may want to explore briefly, before
using only one in more detail. This is also true of accessing the graphical content on the Worldwide Web.

Figure 2: Tactile Diagrams, consisting of raised edges on flat background to be felt tactually. Retrieved from http://access-ed.r2d2.uwm.edu/Virtual_Campus/Tactile_Diagrams/

To address these limitations, researchers have proposed the development of computer interface devices that can be used to provide virtual access to these diagrams digitally, in a manner that is very convenient and efficient to use (Way & Barner, 1997). One of such devices that are very commonly proposed is refreshable tactile displays (Vidal-Verdu & Hafez, 2007). See Chapter 2 for details about the other devices. Typically these displays consist of multiple, dynamically changing actuators that provide some form of tactile feedback (raising, lowering or vibrating pins) under the finger tips of the users to indicate the different features present on the diagram.
Some commercial displays, such as made by Metec, AG (2010) and KGS America (2007), consist of moderately large matrices of pins that can be raised or lowered (Figure 3). These displays are capable of raising selected pins on the display simultaneously to represent the outlines of a raised line picture. As with all refreshable displays, a single display can provide access to multiple diagrams in sequence and this can occur very quickly. However, these devices are very expensive and, as they have many mechanical parts, are potentially difficult to maintain.

Figure 3: Refreshable haptic displays. HyperBraille by, metec AG 2010.

Alternately, some research groups (Jansson et.al., 2006; Owen et.al., 2009; Petit et.al., 2008; Wall & Brewster, 2006; Ziat et al., 2007) have suggested using smaller refreshable displays (Figure 4 a-b) that are cheaper, portable and require easier maintenance. These devices, instead of providing simultaneous access to the entire virtual
diagram, allow the user to actively move a position sensing device (either existing along with the refreshable display or separate to it) within a display area. The position sensor senses the location of itself within a virtual diagram and then the created feedback device provides localized tactile feedback by moving (raising or lowering, laterally moving) the individual pins as appropriate for the local area of the diagram encountered. These refreshable haptic displays can also be used to create dynamic tactual stimuli (i.e., tactile waveforms or animations, e.g., Pietrzak et.al, 2009; Petit et. al., 2008) by using a combination of vibrating pins or patterns which are more salient tactually as compared to statically presented feedback. Even though these devices have many advantages, they are still not widely accepted by the community of blind or visually impaired individuals. We strongly believe that the main issue is not with the device but the way it is used to access visual diagrams.

Figure 4: Smaller display refreshable haptic displays. (a) Vertical pin movement display device. (Owen et. al., 2009) (b) Latero tactile display device (Tactile labs, 2009).
The first issue to consider is that haptics is not vision. As a result, even for simple visual diagrams, in order to make physical tactile diagrams usable many details must be either removed from the diagram and/or, to make them clearly perceptible, magnified for exploration and interpretation purposes (Edman, 1992). The main reason for these modifications is that the haptic system has limited abilities to process line drawing as compared to the visual system (Lederman et al, 1990).

The second issue to consider is that this process of conversion is typically done by sighted individuals, which further limits the accessibility of the diagrams. During this conversion process, dependent on the specific current need for the diagram user, some or many details may be removed from the diagram. This has a potential to hamper independent learning from exploring a diagram, essential for the overall growth of an individual. Hence, we believe that the usability of refreshable haptic displays can be further improved by developing computer applications to: (1) perform all the visual to tactile conversion steps typically done by sighted individuals and (2) provide access to the entire visual information in a manageable fashion by allowing users to manipulate the diagram to compensate for the inherent issues of the haptic system based on the current and changing needs of the user.

One of the limitations of the haptic system that needs to be managed is its lower spatial resolution (as compared to vision), which results in a reduced ability to resolve spatial details in diagrams. The spatial acuity of touch in our fingertips (approximately 1mm) is notably inferior to that of vision in our fovea (approximately 0.15mm from a
distance of 0.5m). Another limitation of the haptic system is the serial based nature of processing 2D geometric information, such as raised line tactile diagrams. Unlike vision, where the user can acquire the entire graphical information in a simple glance (i.e., in parallel), with haptics, the user has to first find the contours on the diagram, then use contour following strategies and then, finally, integrate all the information to make a mental model of the diagram (Lederman et al., 1990).

A commonly used method by individuals who create tactile diagrams to compensate for the problem of lower spatial resolution is to enlarge the diagrams, which sometimes, due to the limited size of the paper, results in dividing the diagram into multiple pictures (Edman, 1992). This in turn makes the content more complicated to use as a user must manage and track multiple diagrams in order to explore the diagram content. The advantage of haptic displays is that a zooming application can be used for the same purpose, allowing the users to start with the overview of the diagram, just like any visual diagram, and then “click” on the point of interest to enlarge. A user can then either further “click” to enlarge the local area of the diagram or return back to the original diagram.

Several research groups (Magnuson & Rassmus-Grohn, 2003; Walker and Salisbury, 2003; Ziat et al., 2007) have previously applied visual zooming methods to solve this issue when used with haptic displays. However, we think there are several issues that make the zooming process using haptics more difficult as compared to vision (see Chapter 2 for more details). Therefore, in this study, we propose the development of an improved zooming method for the use with haptic displays by individuals who are blind or visually impaired.
For compensating the other limitation of using haptics, namely the serial based nature of processing 2D geometric information, the most commonly used method is to simplify the diagrams (Hasty, 2009). From previous observations (pilot studies) and discussions with individuals who create tactile diagrams, we have identified two basic types of image simplification techniques, boundary simplification and contextual simplification, commonly used with tactile diagrams. These are chosen either together or alone based on the need of the user.

For diagrams where the overall shape of the objects or its subparts is of interest, but not the details, boundary simplification is used. This method very simply removes the unnecessary details present on the boundary of the diagram, which might be distracting and cognitively demanding when exploring the shape using touch. For example, for a map of a country, if the question is to name the country, only the coarse shape of the boundary is of interest and fine details (i.e., nooks and crannies) on the boundary are unnecessary. For physical tactile diagrams, a new diagram with simplified boundary is redrawn, which is a time consuming and complicated process. However, a computer program can be used to perform the same task with additional advantages. The boundary of interest can be simplified to various levels using boundary simplification methods (see Chapter 2 for more details). The most simplified boundary can be first presented to obtain the overall shape of objects and, then, with a “click” of a button more details on the boundary can be added if more precise information is required. It should be noted that this dynamic control is not possible with physical tactile diagrams.
Similarly for diagrams where there may be many different objects and object parts, contextual simplification is commonly used. This method is also sometimes referred as decluttering and is needed so that the user does not become overwhelmed by the amount of information and is, therefore, not able to process it. Using this method, a creator of a tactile diagram very simply removes the unnecessary details present on the diagram not required for the current questions being asked. For example, for a map of a city consisting of buildings, roads, monuments and parks, if the question being asked is which monument is close to the park, the presence of other details are unnecessary and distracting. A diagram containing only monuments and parks is required and created, but if the question changes, the same diagram becomes useless. We think computer methods can be used to automatically parse the diagram into individual layers of information present in the diagram (see Chapter 2 for more details). Then the user can be allowed to dynamically control the features to be presented on the diagram using a button “click” on demand. Simplification is necessary due the limitations of haptics, but putting it under a user’s control allows self sufficiency and independent access to whatever information they desire from the original visual diagram.

In this study we present several experiments that were performed towards the development of an automated haptic user interface (AHUI) tool, which, based on the request of the user, performs desired actions on the diagram to compensate for the inherent limitations of haptics when using refreshable haptic displays, without any outside intervention. The entire study was divided into two main parts (shown below) for making individual studies tractable.
(1) Testing and development of a magnification tool, to solve the issue of the lower spatial resolution of haptic system.

(2) Testing and development of simplification tools to solve the issue of the serial based nature of haptic system.

Towards the first goal, a series of three experiments were conducted, which were peer reviewed and published in various journals and conferences. In Chapter 3, we present the first study, where we presented and tested the first iteration of an automated intuitive zooming algorithm to solve the problems of using visual zooming techniques with refreshable haptic displays (Rastogi & Pawluk, 2010b). The proposed zooming algorithm was designed to automatically choose for the user only zoom levels with significant differences based on the content of the diagram, preserving the cognitive grouping of information their by making “intuitive” sense, using wavelet analysis. We found that participants liked the idea of zooming in general and they found intuitive zooming usable. However, the proposed zooming algorithm did not isolate the objects properly, occasionally clipping them. In addition, one of the major limitations of this algorithm was that it assumed that the diagram consisted of a single boundary, which restricted its use on a variety of diagrams.

In Chapter 4 we present the second study, where we proposed and tested the next iteration of an improved haptic zooming algorithm, capable of automatically selecting the zoom levels depending on object-subobject relationships in a multiple boundary visual
diagram (Rastogi & Pawluk, 2012a). The improved zooming algorithm solved the issues of
the previous algorithm (Chapter 3) and had more features, such as auditory feedback
(beeps) to indicate if there was nothing to zoom on.

In chapter 5 we present the third study, where we conducted a comprehensive
experiment to compare the improved, automated, intuitive zooming algorithm with
conventional step and logarithmic visual zooming algorithms (Rastogi & Pawluk, 2011). In
this study we present the improved zooming algorithm in detail. We found that the
proposed zooming algorithm performed significantly better as compared to the step and
logarithmic zooming. We also found that participants found our zooming method more
usable as compared to others.

Towards the second goal, in chapter 2, we discuss in detail different methods and
techniques that can be used for an automatic simplification tool. However before the
development of the automated tool, in Chapter 6, we present a preliminary user study that
was conducted to investigate the utility of boundary and contextual simplification (not
automated), using a refreshable haptic display before the development of a comprehensive
automated simplification tool (Rastogi & Pawluk, 2012b). We found that performance
improved for both the simplification methods, showing the need for the development of an
automated simplification tool. However, during testing we found that many participants
had difficulty perceiving overlaying sets of features that were presented to the users when
performing the testing tasks.

In Chapter 7, we present a follow up study that was conducted to compare the
effectiveness of different presentations methods for accessing overlaying information
(Rastogi & Pawluk, 2012c). Three types of presentation methods were used: tactile tactile toggle (TTS), tactile tactile overlap (TTO) and tactile sonification overlap (TSO). For all methods, several possible tactile and sonification rendering parameters were considered. As there were too many combinations of rendering parameters to examine completely, we first performed a small preliminary study to examine how sensitive the results would be to the rendering parameters chosen. We then chose a single combination of parameters for each method. We found that the performance was the best when using the overlapping method using different modalities. For tactile only methods, using the toggle method was surprisingly preferred by the users as compared to the overlapping method.
2. BACKGROUND

2.1. PHYSIOLOGY OF HUMAN TOUCH

Our human body consists of five senses: vision, audition, olfaction, taste and touch. These senses provide humans the capability to perceive different objects in their surroundings and to interact with them. All of these senses have the ability to work individually, but have some overlapping fields. We unknowingly rely on a combination of these senses to identify objects around us when one or more of the other senses are obstructed. For example, when trying to identify an unknown object without vision, one could use touch to extract valuable physical information like, shape, size, texture, compliance and thermal properties. In this study, our focus will be on the sense of haptic perception, which is a combination of two senses: the kinesthetic sense and the cutaneous sense (Loomis & Leaderman, 1986). Individuals, who have lost their sense of vision, rely heavily on haptic sensory system for most of their daily activities.

In the following sections of this chapter, we will first present the haptic sensory system and its parts in detail. This will be followed by a discussion about the usability of the haptic system in identifying unknown objects in the real world (2D,3D). We will then
present conventional methods and techniques that are currently being used to access visual diagrams, the major focus for our study. In the end, we will discuss methods and applications that can be used to improve the performance and usability of these haptic displays. Throughout this work, we will be using visual diagram and graphical information interchangeably.

2.1.1. HAPTIC SYSTEM

2.1.1.1. CUTANEOUS SENSE

The skin is one of the most abundant and heaviest organs in our body. The cutaneous sense senses the mechanical indentations or stimulations produced on our skin. There are four types of mechonoreceptors present in our body that respond to this external stimulation, they are: Merkel cell neurite complexes, Meissner corpuscles, Ruffini corpuscles and Pacinian corpuscles. All of these receptors can be found at different layers on the skin (Figure 5): the epidermis (merkel), dermis (meissner, ruffini) and subcutaneous tissue (pacinian). These receptors have different physical properties and respond differently to different types of external stimuli on the skin, such as brief touch, prolonged touch, vibrations and so on. These receptors in general can be categorized based on three factors: the rate of adaptation and the receptive field (Figure 6). All of the receptors differ in their receptive fields (small and large) as shown in Figure 7.
Figure 5: Different layer of skin and mechanoreceptors (Vallbo & Johanasson, 1984).

Figure 6: Innervation responses of the different mechanoreceptors for the same mechanical stimulation (Vallbo & Johanasson, 1984).
Merkel cell complexes consist of disk like receptors that can be found present at the basal layer of epidermis, right above the dermis layer. These end organs are associated with slowly adapting type 1 (SA1) nerve fibers, with a smaller receptive field of around 2-3mm (Johnson, 2001). These SA1 receptors are sensitive to sustained touch or pressure, being most sensitive at lower frequencies (0.4-3Hz) on the skin (Johnson, 2001). Meissner corpuscles are oval disk shaped and can be found in the superficial dermis layer of the skin (Figure 5). These are fast adapting type 1 (FA1), with a smaller receptive field of 3-5mm (Johnson, 2001). These FA1 receptors are most sensitive to lower frequency vibration (<50Hz) and respond to only the dynamic component of mechanical stimulation, making them more sensitive to changes in texture and poor at discriminating fine spatial details.

Ruffini corpuscles consist of branched fibers inside a spindle shaped structure and can be found at the lower dermis layer of the skin (Figure 5). These are slowly adapting (SA2) receptors, have larger receptive fields almost five times larger as SA1 (Figure 7) and respond to higher frequencies of 100 to >500Hz (Jones & Lederman, 2006; Johnson, 2001). These SA2 receptors respond to deep skin stretch and are poor at detecting light skin deformation, making them less sensitive as compared to SA1 for detecting skin deformations. Their primary purpose appears to be to detect skin stretch, which is thought to be associated with the detection of the direction of stimuli and accurate measurement of the position of joints (Jones & Lederman, 2006). Pacinian corpuscles are onion shaped receptors located deep in the subcutaneous structure of the skin (Figure 5). These are fast adapting type 2 (FA2) receptors, having a very large receptive field, making them insensitive to distinguishing spatial details. These are most sensitive to much higher
frequencies raging from 200Hz-800Hz, having a non linear response curve as a function of displacement vs frequency with a maximum sensitivity around 300Hz (Prokse & Gandevia, 2009; Verrillo et al., 1969).

Figure 7: Receptive fields of the mechanoreceptors on human hand (Vallbo & Johanasson, 1984), a) Meissner (FA1), b) Merkel cell (SA1), c) Pacinian corpuscles (FA2), d) Ruffini corpuscles (SA2).

2.1.1.2. Kinesthetic Sense

The kinesthetic sense can be simply understood as the sense of position in space or proprioception. In our body this sense provides us with feedback about posture based on the position of the hand, limb, torso and so on. One of the mechanoreceptors in combination with the muscle fibers contributes to this sense of proprioception. Both
muscle spindles and Ruffini corpuscles (SA2) receptors contribute majorly to our sense of kinesthesia, based on both the position and movement of the different parts of the body (Jones and Lederman, 2006).

2.2. HAPTIC EXPLORATION IN OBJECT IDENTIFICATION

Haptic exploration of any objects or scenes uses a combination of both the cutaneous and kinesthetic sense. When exploring 2D raised edges diagrams, individuals use their fingers to feel the raised edges in the diagram (cutaneous) and then follow the edges (kinesthetic) to stitch together a mental picture of the diagram being explored. Magee and Kennedy (1979) found that kinesthetic information was important for identifying outline shape of the objects. However cutaneous sense was used during the free exploration (active exploration) to determine the raised edges and during exploration. But, during passive exploration, where another individual holds the fingers of the users and traces the outline of the objects, performance was found similar as compared to active exploration (D’Anguilli et.al., 1998; Magee and Kennedy, 1979). Hence even though both the senses are need for active explorations, for the task of outline shape identification kinesthetic sense is solely very important and masking it might affect the performance of the users.

Question comes if one or more fingers on the same hand or multiple hands aid in processing of visual information? Previous research have found no significant different between one and two finger exploration (loomis et.al., 1991) on the same hand. However,
Klatzky and colleagues (1993) found performance difference when using 5 unbound fingers compared to two bound fingers on the same hand. Jansson and Monachi (2003) found that when exploring tactile maps outline using single finger on two hands did not show any significant difference in the performance. Hence based on these results it can be noticed that when exploring outlines of 2D diagrams, it does not matter if more than one finger is used on the same hand. In addition one of the advantages of active exploration is that it allows the uses to make independent discoveries and provide more information unlike the passive counterpart, where the sighted individuals guide the fingers of the users. These were two of our major design factor used for the development of the haptic display device (Owen et.al., 2009).

When exploring unknown 3D objects using haptics, users were found to use both the senses in combination using different exploration strategies (Lederman and Kaltzky, 1987). In another study, it was found that individuals were able to correctly and quickly identify 3D objects using haptics (Klatzky et.al., 1993). During haptic exploration of 3D objects, use of multiple fingers is more helpful as compared to using a single finger (Klatzky et.al., 1993; Wijntjes and colleagues, 2008). However, when exploring 2D diagrams no significant difference was found when using two fingers as compared to single finger on the same hand (Jones and Lederman, 2006; Klatzky and Lederman, 1991). This is mainly because material properties are processed in parallel across fingers, unlike 2D geometric information which is processed serially.

2.3. HAPTIC DISPLAYS
Haptic displays are devices that can be used to provide access to any kind of graphical information, such as objects, maps, shapes, and so on, using one or more senses of the human body. For individuals who are blind or visually impaired, three main types of sensory feedbacks are used by these devices: cutaneous, kinesthetic, and auditory senses for the overall perception of unknown objects or diagrams. However, it is not known if one feedback precedes the other or not, as depending on the situation and preference of the users, either single or combinations of these feedbacks are used (Personal Observation).

Haptic displays in general can be divided into two main types: static displays and dynamic displays. Selection of the type of display used typically depends on various factors like intent of the diagram, frequency of use, subjective need, and so on. Additionally, there are several pros and cons of both the displays that also play a leading factor in the preference of the display type used.

2.3.1. STATIC HAPTIC DISPLAYS

Static displays are the display that does not change during or after the exploration of the graphical information. Most commonly used static displays are tactile diagrams (Edman, 1992; Hasty, 2009; Loomis & Lederman, 1986). Tactile diagrams usually consist of raised edges on a flat background, which provide tactile information about lines or borders in a drawing to the person’s fingertips (Figure 2). The spatial relationship of the objects is obtained by touching and following the raised edges to make a mental model of
objects in the diagram. There are several different types of tactile diagrams that are very commonly used such as, thermoform diagrams, swell paper and hand-made textured diagrams (Figure 8).

2.3.1.1. THERMOFORM DIAGRAMS

These are typically produced by heating and pressing thin plastic sheets on a premade metal mold, resulting in the plastic sheet taking the shape of the mold (Figure 8b). This method is mainly used for large scale production of diagrams. Thermoform diagrams are robust, less susceptible to wear-tear and overall cost of production per diagram is cheap. However, disadvantages of this method are that it requires specialized machines, which are expensive and require regular maintenance. Additionally use of special molds restricts its use for dynamic production of the diagrams for daily use.

2.3.1.2. RAISED LINE DRAWINGS

These diagrams (Figure 8a) are typically are made from a special paper called flexi-paper (Repro-Tronics Inc., 2009). Tactile diagram stencil is first printed on the paper, which is passed through a machine called tactile image enhancer (Repro-Tronics Inc., 2009) which raises the edges of the stencil. This method of production is typically used for smaller scale production at home or office. Advantages of these diagrams are that production of diagrams is easier, convenient and practical for home use. However the
machine used is expensive and does require some form of supervision from sighted individuals during use.

2.3.1.3. TEXTURES TACTILE DIAGRAMS

These are made from textures materials (e.g., fabric, fabric paints, and so forth), where parts of the diagram are represented using different textures (Figure 8c). These diagrams are very commonly produced by sighted individuals at schools or educational environments. Advantages of these diagrams are that they are tactually very salient and can be customized based on the needs of the users. However, the process of creating them is usually time consuming, expensive and requires some form of experience. Additionally, these tactile diagrams are, in general, very bulky to carry around due to layering of different parts using different textures.

Figure 8: Tactile Diagrams, a) raised line, b) thermoform, c) textured
Even though these tactile diagrams have several advantages and are very commonly used, there are certain limitations with them, as discussed below,

(1) The physical nature of these diagrams limits their use in dynamic environments, such as in exploratory data analysis, where individuals might come across many diagrams that they may want to explore briefly, before using only one in more detail. This is also true of accessing the graphical content on the Worldwide Web.

(2) All these diagrams are very bulky to carry around. A single diagram can range from 2mm and up depending on the different layers (textures diagrams). The severity of this problem can be understood by considering an example of a single book used by 5th grader in a class might contain around 100-200 diagrams and they might have several different classes in a single day. Hence creating, carrying and keeping a track of the tactile version of their visual counter parts might be very tedious (Hasty, 2010). This problem is not only physical but psychological as it might make them being ridiculed by their sighted peers.

(3) Limited repeatability, as the same diagram might not be used by different individuals for the same class like for example, same map of country for a 5th grade student might need to be much simpler having less details as compared to a 10th grader, who might need more complex version of the diagram with more details (Hasty, 2010).

(4) Production cost and need of a sighted individual for creating these diagrams, reduces the self independence of the individuals who are bind or visually impaired.

2.3.2. DYNAMIC HAPTIC DISPLAYS
These haptic displays by their design (in contrast to static displays) allow the users to work in dynamically changing environments (for which physical tactile diagrams are slow and cumbersome). These displays also allow the users to access and manipulate these visual diagrams on demand (Dargahi & Najarian, 2004; Jones & Lederman, 2006; Levesque, 2005; Wall & Brewster, 2006). Unlike the physical counterparts actuators are used to provide tactile feedback on the fingers of the users about the local virtual graphic information displayed on the computer screen. These displays are typically capable of providing variety of tactile feedbacks, such as forced feedback, vibrating pins and so on.

Many different types of haptic displays have been both developed and proposed, as well as guidelines for their use has been recommended for a wide variety of applications (Hayward et.al., 2004; Hayward & MacLean, 2007; Jones & Sarter, 2008; Way & Barner, 1997). These displays can be divided into two main types; single point contact display and distributed point contact display.

### 2.3.2.1. SINGLE POINT CONTACT DISPLAYS

These haptic display devices in general consist of a stylus or a knob that the users can hold and move around in the real world with 2-6 degrees of freedom (Figure 9), sensors track the position of the knob and corresponding local information of the virtual graphical diagram such as, raised edges, grooves, textures and so on is that provided to the user using tactile feedback. Several different types of point contact display device are
commercially available (e.g., the PHANTOM, Sensable Technology Inc.; the Wingman forced feedback mouse, Logitech Inc.; Falcon, Novint Technologies, Inc.).

Figure 9: Different single point contact haptic displays, (a) Phantom (Sensible Technology Inc.), (b) Falcon (Novint Technologies, Inc.).

2.3.2.2. DISTRIBUTED POINT CONTACT DISPLAYS

These haptic displays unlike the previous consist of multiple actuators that provide multiple contact stimulations on the fingers of the user. Advantages of multiple individually controlled actuators are, (1) It provides access to more spatially distributed information (Lederman & Klatzky, 1987) which would not be possible with the single point contact displays and (2) several different types of tactile renderings can be provided, like patterns (Petit et.al, 2008) making them tactually more salient. In general these devices consist of two main parts, (1) position sensing part that detects the position of the hand or the area can be actively moved by the user and (2) tactile display part that provides the tactile feedback about the information being explored.
Several different types of commercial haptic displays have come and gone, due to several design challenges. One of the most well known devices by the blind or visually impaired community was the Optacon (Telesensory Systems Inc.). This device was developed to provide access to visual text information using the refreshable display. This device consisted of a camera that can be moved over the visual text information using one hand (Figure 10). The information was processed by the device and rendered to the user using a distributed refreshable display (6x26 pin array) vibrating at 230Hz on the other hand (Figure 10). However, their was a steep learning curve to this device, resulting in only certain portion of the blind or visually impaired community to be able to learn and use the system, where as the other individuals didn’t like the device. In addition, it was difficult to maintain and was also very expensive.
Another device that was designed in the same principle, but used mainly for providing access to visual diagrams was VTPlayer (Virtouch Inc.). This device was designed to work similar to computer mice, in addition of providing tactile feedback about the information displayed on the screen. Position of the device was tracked using an optical sensor and tactile feedback was provided on two fingers using the adjacent 4x4 matrix of pins (Figure 11). Advantages of this device was that it was, cheaper, had less mechanical parts, provided both the cutaneous and kinesthetic feedback on the same hand providing
better dexterity and provided binary output raising the pins either up or down having less adaptation, unlike the optacon where they vibrated at 230Hz resulting in tingling feeling.

Figure 11: VTPlayer (Virtouch Inc.)

Even though VTPlayer had several advantages, it was still not widely accepted by the blind or visually impaired community. Rastogi and Pawluk (2010a) found this was due to two main design issues resulting in reduced usability. The design issues were (1) the device was relative positioning rather than absolute and (2) in coordination between the position sensor and tactile display resulting in angular rotation errors. They proposed solutions to solve these issues and, found significant performance improvements and
reduction in overall exploration time with modified VTPlayer. However, implementing those solutions added extra costs to the already expensive VTPlayer and in addition, they found that the device hardware had inherent time delay of 200ms between device sensing the visual information and tactile pins responding.

To overcome these issues, Owen and colleagues (2009) developed a low cost *refreshable haptic display* device that was under $400 ([1](#)). This device worked in the same was as VTPlayer. The main differences between this device and VTPlayer were, (a) for the actual tactile display, a single refreshable Braille cell (Metec, AG) consisting of a matrix of eight tactile pins (4x2) was used (Figure 12b). This was done, as Jansson and Monachi (2003) found that performance does not change using one or two fingers of the same hand and also to reduce the cost. (b) A graphics tablet (Adesso 12000; Adesso Inc., 2011) was used to keep track of the position of the tactile display (Figure 12a), as unlike an optical mouse it is an absolute rather than a relative pointing device. For this a transmitter circuit tuned to the given tablet was mounted directly under the tactile display to improve spatial collocation between the kinesthetic and tactile information (Rastogi & Palwuk, 2010a). (c) The entire circuit was mounted inside a small hollow mouse case to maintain the low cost and good ergonomics, unlike VTPlayer which was very large and hard to hold (Figure 11). (d) A frame was used around the device to prevent the users from moving out of the tablet screen.

The device reduced the time delay between refresh rate of the tactile pins and position sensing to 2ms and added additional feature of providing tactile vibration feedback from 0-300Hz. However this device still had limited tactile temporal bandwidth
limiting the tactile patterns that can be provided using the device. To solve this, Patric and Pawluk (2011) added an additional feature of raising the tactile pins to variable amplitude (3 levels) in addition of accurately providing temporal feedback.

Figure 12: Low cost, Variable Amplitude Haptic Display device.

2.4. INFORMATION VISUALIZATION USING REFRESHABLE HAPTIC DISPLAYS

The presentation of information graphically is important for conveying the spatial relationship between parts in diagrams, such as, navigational or geographic maps, building layouts, and illustrations of objects and object scenes. However, the amount of information that can be conveyed in haptic graphics is typically limited in current presentation methods, discussed above, due to the haptics poor spatial resolution and serial based nature of processing 2D information. This results in limited access to the details present in the
diagram. We think the ability of refreshable haptic display to interact with computers though can be used to compensate for these limitations, increasing it usability. One can start with an overview of an unknown visual graphic spanning the working area of the device, then depending on the question being asked or to understand details of interest during independent exploration, users can either magnify or simplify the details present on the diagram dynamically using a combination of button or keys present on the haptic display or keyboard.

2.5. MAGNIFICATION IN HAPTIC INFORMATION VISUALIZATION

Magnification plays a very important role in visual to tactile diagram conversion process and is mainly used to compensate for the lower spatial resolution of haptic processing as compared to vision. Magnification with reference to tactile diagram simply means, physically making the details present on the diagram larger to be tactually perceivable (Edmand, 1992; Hasty, 2009). In this section we would first present the different types of zooming techniques that are currently being used or have been investigated for use with haptic displays. We will then present a discussion on the problems associated with using visual zooming on haptic displays and propose a method, improved haptic zooming algorithm, to solve those issues.

2.5.1. VISUAL ZOOMING WITH HAPTIC DISPLAYS
Zooming is very commonly used on visual diagrams for examining details that cannot be resolved with the eyes. There are two major types of visual zooming techniques, step and smooth zooming, that are most commonly used on visual diagrams. Using step zooming for every request “click” on the device, objects become larger in distinct predefined (linear or logarithmic) steps. Whereas, with smooth zooming users can access wide variety of zooming scales by scrolling the wheel on the user interface device or by clicking on a visual scale to select the amount of zoom required.

Several research groups have directly used these with haptic displays to access visual diagrams (Magnuson & Rassmus-Grohn, 2003; Walker and Salisbury, 2003; Ziat et.al., 2007). Walker and Salisbury (2003) briefly described an implementation of panning and smooth zooming, with force feedback “detents” to indicate discrete zoom values, for navigating a 3-D topographical surface. Magnuson and Rassmus-Grohn (2003), examined the performance using logarithmic step zooming along with a variety of panning, on a model consisting of houses, roadways and walkways. They used spoken sounds (auditory feedback) for accessing details about the objects on the diagrams. They tested the zooming independent to use with panning. They found that all participants (5 blindfolded sighted and 1 blind) were able to use the four distinct levels of zoom (10%, 25%, 50% and 100%). However, participants rated it to be hard to use (3.4 out of 5 in difficulty).

Similarly, three groups have also investigated the use of linear zooming with the haptic display. Ziat and her colleagues (2007) investigated the ability of the participants to make the distinction between zooming in or out and the use of 10, 100 and 1000 linear steps of zoom to resolve the configuration on the diagram of one, four or nine squares of
the same over all size. They found that participants were able to identify the direction of zoom and used approximately 25 levels of zoom utilized when given the choice. Schloerb and his colleagues (2010) incorporated linear step zooming and two types of panning, as part of a virtual environment system for orientation and mobility training containing a small set of object types. The discrete zoom levels were limited to three (in contrast to, Ziat et. al., 2007) based on the assumption that the user might otherwise lose track of the scale. However, no specific zooming results beyond the ability of the subjects to use the zoom were described.

Schmitz and Ertl (2010) investigated the use of linear zooming on specifically on street maps. However, they state that no fixed zooming levels yielded satisfying results. They proposed, instead, an “intelligent” zoom based on the density of, for example, the streets. However, due to their small sample size, there were no clear results. It should be noted that, similar to Ziat and colleagues (2007), they also described a method of reducing detail when zooming out, but only relevant for street maps. However, none of the studies considered the difference between haptic explorations as compared to visual exploration, which we believe could result in zooming performance of the blind or visually impaired performance being extremely inefficient and frustrating depending on the content of the graphic being explored.

2.5.2. VISUAL ZOOMING VS HAPTIC ZOOMING
In general the process of zooming is the same with or without zooming when used with haptic displays, where the user first scans through the display area, locate the area of interest and then clicks on the user interface device to make it larger, then either continues exploration or clicks further to make it larger. However, there are two main differences that make this process of exploration extremely difficult, time consuming and inefficient when used with haptics alone as compared to with vision. First, unlike vision, where the user can take in a whole picture at once (parallel processing) in a quick glance, without vision, users have to at least explore the diagram using contour following strategy (serial processing) to some extent at any given level before making the decision whether to stay at that zoom level or not. Unfortunately, this process of exploration for accessing such 2D geometric information is very slow, serial and cognitively demanding (Lederman et.al., 1990). Of course, this would not be an issue for diagrams where the zoom levels were chosen appropriately, providing access to details on the diagram as different as possible which are fundamentally different, such as for a map of a country, zoom levels proving access to country, state, cities and so on. However what scales to use would change with diagrams and would not work with other. Hence the key point here is that using a universal predefined set of zooming levels would not be the most efficient way to access details on visual diagrams.

Another issue which is worst is that zooming to a new level may crop pieces of information that should be grouped together (e.g., only showing half of an object). For example, for a diagram consisting of an elephant and mouse standing side by side, zooming on the mouse would center it and make it larger but depending on the zooming
level part of the elephant would still be on the screen and most of it will get cropped. This cropping of the objects can happen due to either clicking at wrong positions on the screen or it can happen depending on the zoom levels making objects very large. This would not be an issue with vision, as the user can quickly realize the problem and take preventive measure to correct it. However without vision it would be hard for the users to realize that cropping has occurred and particularly when exploring unknown diagrams it would be extremely difficult to interpret the cropped details. Scrolling can be used to correct this, but it would still be a difficult process as the user would have to serially explore before realizing if they scrolled too much or too little, adding to the time of exploration and frustration.

Therefore, we believe there is a need of an improved zooming method that would prevent redundant levels of zooms by automatically selecting “intuitive” levels of zoom, avoid cropping of the objects, preserve the relational groupings of the objects, prevent accidental zooming and provide auditory feedback, for use by individuals who are blind or visually impaired. However, what zoom levels are appropriate are expected to be dependent on the information content present in the diagram and may even vary within different areas of a diagram (e.g., such as zooming in on an elephant versus a mouse). Additionally auditory feedback is required to make the users aware of the changes on the screen. The other feature of preventing zooming on area where there are no objects present is also essential as it would aid the user during the exploration, reducing unnecessary exploration time and frustration.
In this study we considered two methods that could potentially be used towards this proposed automatic intuitive zooming algorithm. First method was based on continuous wavelet analysis. This method was considered as (1) it could potentially be used to perform boundary simplification on the diagrams (required for second aim) and (2) its simpler and faster to compute. This method works by using the continuous wavelet transform coefficients to detect the clustering of the information over a single scale, which could then used to determine individual intuitive zoom levels (see chapter 3 for more details). Another more complicated method that was considered involved detecting and arranging all the boundaries present in the diagram in a hierarchical tree structure automatically and then using mathematical transforms to make decisions about clustering or grouping together required for the intuitive zooming (see chapter 4-5 for more details). This method was more complex to perform and slower to compute, hence before implementing it, we decided it would be logical to implement and test the fairy simple method for the effectiveness and need of intuitive zooming by individuals who are blind or visually impaired. Based on the results, we think the second algorithm which would be more robust and could potentially be used with more complex and varied diagrams should be developed.

2.6. SIMPLIFICATION IN HAPTIC INFORMATION VISUALIZATION

Diagram simplification is another method that is a very essential part of the visual to tactile diagram conversion process required mainly to compensate for the serial based
nature of haptic processing. The standard process of diagram simplification is to omit some (or even much) of the material (Hasty, 2009). This simplification process, as discussed earlier, can be mainly classified into two types, boundary simplification and contextual simplification, performed based on intend of the diagram. In this section we would discuss in detail different computer methods that can potentially be used to perform simplification on the diagram.

2.6.1. BOUNDARY SIMPLIFICATION

This method of simplification is typically used for tactile line diagrams where the overall shape of the object is of interest. Tactile diagrams used for this kind of simplification usually consist of single or multiple boundaries, where the presence of the small nooks and crannies on the boundary distracts users from determining the general shape due to: (a) the increased difficulty in tracking the boundary and (b) the increased cognitive load in serially integrating all the information. Thus for physical diagrams by presenting the user with a smoother simplified boundary, overall exploratory process is improved, in both correctness of the answer and response time. We suggested that computer applications can be used to dynamically perform these simplification, presenting the user with the most simple diagram first and allowing them to add details back on the diagram on demand.

Many research groups have extensively investigated the process of boundary representation and several reviews have been presented for varying applications (for details
refer, Mokhtarian & Mackworth, 1992; Mingqiang et.al., 2008; Zhang and Lu, 2004; Gonzalez & Woods, 2008; Gonzalez et al., 2009). Although these methods were designed for different applications, like object identification, matching and so on. We think that the ability of these methods to capture the shape details can alternatively be used to simplify the shape by manipulate its parameters. In general the way these boundary representation techniques work is that a mathematical transform is used to represent the shape of the contour by what are called shape descriptors. Hence, by manipulating these descriptors results in changes in the overall shape of the contour. For the use with tactile diagrams these methods can further be classified into two types; line and curve simplification methods. The fundamental difference being that one method simplifies the boundary of the objects containing into smoother curves and other into polygonal shapes.

Straight lines are in general easier to track than more convoluted lines and, likely, much easier to cognitively process (personal observations). In addition, at the very least, straight-line distance estimates are also known to be distorted by the pathway tracked between the points (Lederman et.al., 1987). It is hypothesized that questions involving the general, rather than the precise shape, of a boundary can be performed faster and more accurately using a simplified polygonal (i.e., straight line) version of the boundary. However, the more convoluted pathway should be available for more precise questions if needed. Hence it would seem desirable to implement both the simplification methods and let the user choose based on the diagram and question being asked.

2.6.1.1. CURVE SIMPLIFICATION
For curve simplification many different types of visual simplification techniques could be used, such as; (1) Fourier descriptors (Ai et.al., 2008), simplification using this method is obtained by determining the Fourier coefficients of the space vector (X-coordinate + i* Y-coordinate), providing the global frequency content of the boundary. By removing N coefficients (where N= 0 to half of the boundary points), padding the removed coefficients with zeros and reconstructing the boundary, multiple levels of simplification can be obtained. (2) Curvature scale space (Mokhtarian & Mackworth, 1992; Mokhtarian & Bober, 2003), simplification using this method is obtained by convolving the space vector representing the curve by the Gaussian function g(t,σ). Varying the width of the Gaussian by changing the sigma (σ) removes the small details from the curve, resulting in smoothing of the curve over multiple levels. (3) Wavelet scale space (Chuang & Kuo, 1996; Wang Yu-Ping et. al., 1999). Wavelet scale space analysis on the other hand uses wavelets, such as haar, coiflets (coif), biorthogonal (bior), reverse biorthogonal (rbio) and so on, which are scaled and translated over the space vector to obtain the wavelet coefficients. Most commonly used WSS technique is discrete wavelet transform (DWT), which uses filter banks consisting of a low pass and high pass quadrature mirror filters. When the samples, space vectors, are passed through these filters, they provide approximation and detail coefficients, corresponding to the low and high frequency content of the shape information. Simplification is obtained by removing the detail coefficients and reconstructing the boundary. These are some of the methods that can be used for our
application, see reviews on boundary representations for others (Mokhtarian & Mackworth, 1992; Mingqiang et.al., 2008; Zhang & Lu, 2004).

### 2.6.1.2. LINE SIMPLIFICATION

For line simplification, method that can perform polygonal approximation can be used. The way these methods work it that they assume that any closed boundary can be accurately approximated by having the same number of vertices in the polygon as the number of points in the boundary. Then, by reducing the number of vertices, the boundary becomes a simpler polygon, hence simplified. The most conventional techniques used for polygonal approximation are the minimum perimeter polygon (MPP) method and the chain code (CC) approximation (Mingqiang et.al., 2008; Zhang and Lu, 2004; Gonzalez & Woods, 2008; Gonzalez et al., 2009). To determine the reduced polygon by these methods, a grid of square cells is placed on the image, where each cell covers NxN pixels of the image. The size of the cells is increased to produce a simpler polygon. All cells that contain the boundary pixels are marked. The simpler polygon is then constructed based on the rules for that approximation. With the CC approximation, a 4 connected chain code which assigns a number (0-3) for the four directions (right, north, left, south), is used to get a vector representing the boundary of the diagram. With the MPP method, the resultant boundaries, at varying levels, resemble shapes that can be approximated by fitting an elastic band (minimum perimeter) around the detected vertices. The resultant shape can be very closely approximated by a polygonal boundary.
Now the question comes within each method, line or curve, which of the above discussed techniques should be used? Although it would be desirable to implement all the methods discussed above in the boundary simplification tool, we have found that the golden rule when developing application for individuals who are blind or visually impaired is “LESS IS BETTER” (Hasty, 2009; Johnson, 2010). Hence, we think testing need to be done to select the best methods that can be used to perform these simplifications. Some of the decision criteria’s that should be considered when selecting these methods are; (a) easy and fast to implement, (b) allow simplification of the boundary over multiple scales, (c) result in simplified curves that are fundamentally different, which for our application means tactually different and (d) the resultant shapes closely resemble visually apparent simplified versions of the original diagram.

2.6.2. CONTEXTUAL SIMPLIFICATION

This simplification method works similar to “filter” and “relate” tasks in visual information exploration (Dykes et.al., 2005). The idea behind this simplification method is to allow the users to remove material from the diagram not needed for the particular context being used at that instance of use, as it might be too complicated and distracting to be present on the diagram. By removing the unnecessary information for the particular question, it is hypothesized that users will be able to respond quicker and more accurately.
However, the other pieces of information are still available and can be added in a similarly manner if needed on demand.

There are several different types of diagrams that can be used with this simplification tool. In this section, we would be considering a single example of geographic maps for both simplicity and frequency of use with this kind of simplification. We suggest that performing this type of simplification automatically would require four main steps;

(1) Detecting the features present on the diagram, this can be very simply done by using the key present on the diagram. For diagrams where the key are not present image segmentation tools can be used to detect the different features.

(2) Locating the different features on the diagram. This for symbols would mean detecting the location but for features represented by textures or patterns would mean detecting the spatial shape along with the locations present on the diagram.

(3) Developing a data structure, consisting of individual features as separate layers, with all the required information to identify it later like for example, alphabetical name, Braille characters (if present), size information and so on.

(4) Presenting the processed information to the user using refreshable haptic displays, in a manner that is easy to use and provides auditory feedback about whenever required.
We suggest that the steps 1-3 should be performed before the step 4 to prevent any time lag during the user’s request and the display on the device. The first two steps of feature identification and location detection typically would involve the detection of the spatial location, size and shape of different types of feature present at different areas on the diagram. There are many different types of representations that are used in visual diagrams such as, (1) homogeneous color, (2) homogeneous gray, (3) textures patterns and last but not least (4) physical features (e.g., symbols of mountain, oil wells and so on).

The above discussed steps for first two types of features can be easily performed by searching globally for the different homogeneous color/gray pixels (e.g., Figure 13) present at different locations on the diagram and then separating them into different layers consisting of a single value. These can then be displayed on the haptic display allowing the users to add, remove or keep “layers” based on the question being asked. For the third type of diagrams consisting of textures patterns, same technique discussed above can not be used. As the size and shape of the bounding box in the key might not be the same as that shown in the diagram. For these types of diagrams, each pattern would be different and have different variations between the individual pixels. We suggest that a mathematical metric (e.g., similar to Chen et al., 2005) can be determined unique to each texture. Layers can then be created by detecting the textures, using pixels with metric vector values clustered around that of a single texture by means of k-means clustering.
For the diagrams containing physical features (e.g., a picture of a cattle, coal, see Figure 14) we think feature or pattern identification techniques can be used. Many different techniques for this purpose have been developed, such as cross correlation, Bayes, naïve Bayes, k-nearest neighbor and neural networks (Gonzalez & Woods, 2008; Polikar, 2006). In general the way these techniques work is that spatial details of the feature of interest are obtained by determining the correlation coefficient of the key or a template over the entire diagram. The points containing a high correlation coefficient (~1), will show the presence of the feature at that location. Here we suggest few of the many other methods that can be used for this purpose. However, when selecting the best methods one must be kept in mind: (1) it is fast to compute and (2) it does not require any form of training of the model or database to match the features. The latter, in fact, does not make sense since each diagram will have different features to be detected.
Figure 14: Map of Brazil with natural resources
The last step 4 involving the presentation of the layers (user interface) is another crucial part of this simplification tool and careful considerations must be made when designing this part of the tool. The main aim of this part of the tool is to make the various menu options, such as adding features, removing features and so on available to the user in such a manner that it is easy to learn, intuitive and less cumbersome. Several research groups have presented design principles that must be kept in mind, when designing user interface for the individuals who are blind and/or visually impaired based on their needs (Alonso et.al., 1998; Jaijongrak et.al., 2011). Additionally providing auditory feedback in combination with haptic feedback should also be considered (Jansson et.al., 2006; Homes et.al., 1996). Homes and colleagues (1996) also found that providing auditory feedback noticeably improved the performance of the participants. In addition to auditory feedback, menu option should also be organized in a tree hierarchy, where menu items on a given tree branch will be presented to the user to select in temporal sequence.

2.7. PRESENTATION METHODS

One important area in using visual diagrams is for information visualization of content such as maps (e.g., geographical, city or floor plans) and atlases (e.g., of the human body), for which they have been shown to be a powerful thinking and decision tool. In previous sections we discussed and presented methods towards making exploration easier and more effective for individuals who are blind or visually impaired. Another issue we
consider in this work is that of effectively presenting overlapping information items when exploring tactile diagrams using refreshable haptic display.

For example, for a geographic map diagram consisting of multiple features (Figure 14), applying the contextual tool discussed above, would divide the diagram into multiple layers one for each feature. These can then be easily presented to the users by assigning unique feedback using haptic displays that are very salient. Hence, when selecting individual details on the diagram that does not have any overlapping areas (e.g., Figure 14; coffee, lumbar and reforesting) individuals would be able to find the regions and interpret them easily, but in situation when the feature on the diagrams overlap (e.g., Figure 14; coal, lumbering and reforesting) it would be very hard to detect the regions unless the feedback modalities are very different from each other. This is not a unique situation, as these types of tasks are very frequently encountered in determining relationships between different items (Plaisant, 2005).

Several research groups have suggested and investigated multimodal feedback that can be used with haptic displays to effectively differentiate features present on maps (Paneels and Roberts, 2010; Nesbitt K, 2000). Paneels and Roberts (2010) in their review suggested that haptics and audition are the two main types of feedback modalities that are frequently used for haptic map visualizations. Jeong and colleagues (2002, 2003) did several studies to investigate the combinations of different modalities, mainly visual, haptic and auditory, that can be used with map diagrams. They compared four major combinations, color-color, color-haptic, color-audio and haptic-audio; they found that haptic-audio performed the best for their response variable. For providing haptic feedback,
tactile vibrations of increasing frequency were used using a Logitech iFeel mouse. Parente and Bishop (2003), in their study, used a combination of static tactile feedback bumps to represent the state boundaries and constant tactile vibrations to represent cities. They found that in informal testing, four blind participants were able to use the system. Burch and colleagues (2011) also found temporal tactile vibrations to be the most effective method within the tactile modality.

Another type of tactile feedback that can be used with haptic map data visualizations was suggested by Jansson and colleagues (2006) where, to make exploration of tactile maps using a haptic mouse (VTPlayer, Virtouch Inc.) convenient, compared performance improvements from using static texture patterns with audio feedback. Interestingly, they found that the performance was better with textured patterns as compared to no patterns. Hence, in summary, based on previous studies and experience with the haptic device developed in our lab (Owen et al., 2009), we think four types of tactile feedback are good candidates to represent features on maps and atlases. They are: static tactile feedback (raise up or down, good for boundaries), static spatial tactile feedback (Tactons; Paneels and Roberts, 2010; Pietrzak et al., 2009), spatial animation tactile feedback (Pietrzak et al., 2009) and temporal vibration feedback (Burch et al., 2011; Ghiani et al., 2009).

Although solely tactile feedback can be used, many research groups have investigated other sensory modalities that could be used with haptic displays (Paneels and Roberts, 2010; Nesbitt K, 2000; Jansson et al., 2006; Homes et al., 1996). One of such sensory modality that is very frequently considered is auditory feedback (Paneels and
Roberts, 2010; Nesbitt K, 2000). Audio feedback is typically used in one of two ways: using text to speech, such as for the name of features, an action performed and so on, or using sonification (Herman et.al., 2011).

Wall and Brewster (2006) investigated the combination of haptic and audio feedback for exploring bar graphs, where the bar graphs were explored using haptic feedback and text to speech was used to provide detailed information. Moll and colleagues (2010) found that using speech sounds with the haptic displays was very helpful when exploring virtual environments. Wang and colleagues (2012) also developed a system for independent access to geographic map diagram with audio feedback about the turn by turn directions using speech feedback.

Sonification on the other hand can be defined as the use of non speech sounds to represent information. There are primarily three different types of sonification commonly considered for applications for people with visual disabilities (Power and Jugerson, 2010): 1) earcons, which are arbitrary acoustic motifs (Brewster et al., 1994), 2) auditory icons, which are like earcons but modeled on “everyday” sounds, and 3) parameter mapping from the data to the display. McGookin and Brewster (2011) found that recollection rate of auditory icons is the highest, but are generally created to have a sound related to what they represent which would mean different icons for different maps. Another possibility is the use of earcons (Brewster et al., 1994). McGookin and Brewster (2011) have proposed and investigated several different types of acoustic dimension that can be used alone or combined for earcons: pitch (perceived frequency), timbre (prevailing quality of a sound,
e.g. brassy), rhythm (duration, rate of change) and/or loudness (perceived amplitude).

These parameters also interact to affect the perception of each other.

Knowing the above, we can use either tactile or auditory feedback or a combination of both types of feedback. The question is what is most effective to present overlapping information? One method that is sometimes used with visual presentation methods is to have two different maps, each with a single set of features. The user is then required to toggle back and forth between the two maps to infer the relationship between the two separate diagrams. Petit and colleagues (2008) used a similar type of toggle method tactually to present information to individuals who were blind and visually impaired. In one diagram they had represented continents and the, in the other, civilizations. However, as this was a brief part of their paper, the usability of the method was not examined.

Another possibility is by representing the two different feature sets by representations that can be effectively interpreted when they overlap. For example, in vision, one set could be represented by color, whereas the other set could be represented by different types of patterns (e.g., different oriented stripe patterns). Finally, the two different sets of features could be presented by two different modalities (e.g., touch and sound).

We think that representing the two different sets of features by two different modalities will perform the best. This is based on cognitive load theory which asserts that the limited working memory associated with a single presentation modality can be circumvented by using more than one presentation modality. However, whether this is needed or not may depend on how easily separable the two sets are in a single dimension.
Moreover, for individuals who are deaf-blind, the use of audition is not an option. Therefore, it is also important to ascertain an effective method that uses solely tactile information. We expect that having two overlapping methods would be more effective than toggling particularly for haptics as, due to the serial nature of processing geometric information, it will be difficult to remember where the features of the previous set were found.
3. AUTOMATIC INTUITIVE ZOOMING FOR PEOPLE WHO ARE BLIND OR VISUALLY IMPAIRED

In this chapter, we present the first study that was performed towards the development of an automated magnification tool for an AHUI. In this study, a novel technique of automatic, “intuitive” zooming of graphical information that was developed for individuals who are blind or visually impaired to access tactile diagrams was presented. The algorithm used wavelet analysis to localize the details of a graphic and then uses methods looking at the clustering of details to decide on the levels of zoom, which are significantly different from each other. As discussed previously, in Chapter 2, this method was chosen as it had an additional advantage that it could potentially be used to perform boundary simplification, required for the second goal, and as it is faster to process. The format of the original published manuscript was changed to fit the requirements of the thesis by VCU, Graduate school.

3.1. PILOT TESTING

The main aim of this preliminary pilot testing was to verify the effectiveness and usability of the advantages of the proposed zooming techniques.
3.1.1. ZOOMING ALGORITHM

Conceptually, the algorithm works by the user clicking on a point on the diagram where they would like to zoom, similar to other zoom algorithms. The algorithm then determines whether there are any details in the graphic locally around that point. If not, the algorithm does not zoom and provides a single auditory beep. If there are details, rather than using a fixed zoom step size, the algorithm determines how the details locally cluster (e.g., a whole object or object part). It then zooms in with a step size that will keep the cluster all in the same image. Then, if the user clicks on the zoomed image, the algorithm is repeated. This continues until the user either zooms back out or no more details are available (at which point the algorithm provides a beep).

The first three components of our algorithm occur before the user begins using the haptic device: (1) the line drawing is converted into a binary image; (2) the contour path is extracted (Mingwu et.al., 2002); and (3) localization of details on the contour is determined. For the latter, continuous wavelet transform (cwt) coefficients obtained with the symmetric Morlet wavelet are used to extract the details, although any symmetric wavelet would suffice.

For the next steps, rather than using scale space analysis to determine the zoom levels, we chose a single scale level, scale 20, and examined the clustering of coefficients corresponding to the details on the contour. The rationale for this was two fold: (1) clustering, as opposed to scale space analysis, is much more likely to produce zoom levels
that are cognitively appropriate (i.e., whole objects or whole object parts); and (2) localization is more accurate using clustering on a relatively low data scale as opposed to scale space methods using higher scales to select the coarsest zoom levels. Scale 20 was chosen as it provided the best description of the details of the contour for a variety of graphics.

For the algorithm, the wavelet transform coefficients at scale 20 are determined and merged to yield the magnitude, $R_{xy}$, and phase of the $x$ and $y$ components of the contour. In order to determine the clustering, the envelope of the local maxima values is extracted. When the user then clicks on a point in the graphic, the closest point on the envelope is found. Then the largest troughs close to that point (determined through an algorithm that space does not permit us to describe) are selected as the defining points of the cluster to be selected to zoom in on. The ‘intuitive’ zoom level is then determined by the boundary box defining the maximum and minimum values of $x$ and $y$ between the index values (cwt coefficients) of the cluster found.

### 3.1.2. PARTICIPANTS

A total of 3 blind and 4 sighted blind folded subjects participated in the study. All blind participants had previous experience with tactile graphics.

### 3.1.3. EXPERIMENTAL STIMULI
For this initial assessment of the concept of automatic, intuitive zooming, two diagrams containing maps of hypothetical buildings were used. Each map contained five universal symbols providing information about some of the rooms (e.g., Figure 15a). For training, a diagram containing the same objects, but at different locations, was used. When exploring the diagram, clicking on an area of the graphic activated the zooming algorithm described above.
3.1.4. EXPERIMENTAL PROCEDURE

Our modified VT Player (Rastogi et al., 2010a), which uses absolute position sensing (in contrast to the original VT Player), was used. Each participant was given training on the device for 45 minutes before testing, during which they were taught to freely explore the training diagram to locate and feel the symbols. Participants were told to ask the experimenter when they wanted to zoom in on where they were in the diagram (for this pilot test only), which the experimenter would activate. They were also trained to interpret the audio beeps indicating whether a zoom occurred. Finally, participants were provided with a raised line drawing key having all the symbols in the tactile graphic.
During testing each subject had to perform two tasks: (1) show the positions of the symbols and (2) identify the symbols. At the end of the experiment they were asked to take the System Usability Survey (Brooke, 1986).

3.2. RESULTS AND DISCUSSION

We found that, for the first task, all participants were able to find the positions of the symbols on the diagrams. For the second task, blind subjects were able to correctly identify 80% of the symbols, whereas sighted blind folded participants were able to correctly identify 90% of the symbols. More importantly, all participants indicated that they could not identify the symbols until they were zoomed, except for one participant who identified one symbol without zooming. However, only one zoom step was required, in contrast to fixed step and smooth zoom modes which would likely require multiple steps of zoom. Participants also tried to zoom in on areas that zooming would provide no further details an average of 5 times. Preventing the zoom and indicating this to the participants reduced the exploration time, which would have been higher if explored with a different type of zooming algorithm.

The System Usability Survey gave a mean score of 71, with 0 being non usable and 100 most usable. Qualitative feedback suggested that most of the problems were with the device, diagrams or complexity of the task, rather than the zooming function. However, all participants said they had a harder time tracking lines at the zoomed level due to the
increased thickness of the lines. In future, we will thin the zoomed lines before displaying the zoomed level.

Future work will include a more thorough testing of the use of our “intuitive” zoom and its comparison to other methods of zoom. In addition, we will also consider the possibility of incorporating “semantic zooming”, which allows details to emerge as the user zooms in. This would help avoid clutter at the higher levels of zoom, which increases the difficulty of interpreting a graphic.
4. TOWARDS AN IMPROVED HAPTIC ZOOMING ALGORITHM FOR
GRAPHICAL INFORMATION ACCESSED BY INDIVIDUALS WHO ARE
BLIND OR VISUALLY IMPAIRED

In this chapter, we present the second study that was performed towards the goal of
development of an automated magnification tool for AHUI. In the previous a preliminary
study, we found that participants liked the idea of zooming in general and found intuitive
zooming usable. However, we found that the proposed zooming algorithm did not isolate
the objects properly, occasionally clipping them, failing one of the major requirements of
the proposed zooming algorithm. Hence, in this chapter we present and test the second
iteration of zooming algorithm that was developed to solve the issue with the previous
iteration of the intuitive zooming method.

4.1. METHOD

The main aim of this study was to examine whether the improved haptic zooming
algorithm we have developed for exploring electronic tactile graphics on a computer via a
haptic computer interface device by individuals who are blind or visually impaired shows
promise for its utility and for determining improvements for the next iteration of the
algorithm. Although the results of our algorithm could also be presented visually (for
those with low vision), in this experiment we focused solely on perception by touch. The use of this algorithm was compared to a control condition in which no zooming was allowed. While using a variety of different graphics would be desirable, studies using tactile graphics particularly on haptic displays are very time consuming. To make this preliminary study tractable, we used a single type of diagram. Building layout diagrams were chosen, due to (a) their frequency of use and (b) the need to perceive details (e.g., identifying universal symbols), where zooming would be potentially desirable or beneficial.

### 4.1.1. HAPTIC COMPUTER INTERFACE DEVICE

The haptic computer interface device used (Owen et al., 2009) consisted of; an electronic Braille cell (Metec AG., 2010) acting as the tactile display, mounted on a mouse case that also has four active programmable buttons (see Figure 12a). To perceive an electronically stored diagram in the computer, the “mouse” is moved over a graphics tablet (Adesso Inc., 2011), see Figure 12b). The tablet allows the computer to record the position of the tactile display by communicating with a radio frequency transmitter inside the mouse case. The computer then determines what position on the electronic diagram each Braille pin corresponds. As a pin passes over a line in the diagram (raised edge), it is first raised (to create the rising edge) and then lowered (to create the falling edge). For this experiment, the four buttons of the mouse are programmed to perform: zoom in, zoom out, home (overview image) and close the diagram.
4.1.2. ZOOMING ALGORITHM

An improved haptic zooming algorithm was developed for all individuals with visual impairments: the focus of this paper is on its potential effectiveness on the tactile perception of diagrams, although it could be used visually as well, either alone or with touch. The algorithm is implemented as a computer program performing its functions without any human intervention. The purpose of this algorithm is to take a computer drawn line diagram, spanning multiple scales of view and automatically create and manage the hierarchy of diagrams needed to view it tactually across these scales, according to our rules described below. The algorithm then interacts with a haptic display device, such as the one described above, to allow the user to explore and navigate the diagram hierarchy by using the location of the device on the current diagram and the buttons on the device.
Two rules are used to create the diagram hierarchy: 1) objects that are close to each other are considered meaningful groupings and are selected as a whole to be represented in a sub-diagram; otherwise, 2) individual objects are represented in each sub-diagram. This is performed recursively on each sub-diagram until all diagrams of the hierarchy are created (Figure 16). For example, in Figure 17, one may start with the overall diagram given in 17a of a cluster of houses with a flower beside each house. The second level of the hierarchy will contain separate diagrams of each house with a flower following rule 1 (Figure 17b). Underneath each house-flower diagram in the hierarchy will be diagrams for the house and flower individually following rule 2 (e.g., Figure 17c). Further levels of the hierarchy will be created for the components of the houses and flowers.
Figure 17. A portion of the diagram hierarchy.

After the diagram hierarchy is created, the user can then interact with the computer program using a haptic display device to navigate through the diagrams (Figure 18). The user clicks on the zoom-in button to access the next level of the hierarchy based on the location of the mouse pointer on the current diagram. If there is actually a sub-diagram to access in the hierarchy corresponding to that location, the sub-diagram is presented and a double auditory beep occurs. If there is no sub-diagram to access, a single beep occurs and nothing happens. When the user zooms out, they are returned to the previous diagram they were exploring before the current zoom in.
This algorithm is expected to be primarily useful for pictures, system and device layouts, and building layouts. The key feature for its use is that the given diagram can be organized in terms of a hierarchy of objects and sub-objects that can then be traversed. Other types of diagrams, such as line graphs, where zooming is on a part of a single line likely would fare better with our initial algorithm based on wavelet analysis (Rastogi & Pawluk, 2010b) as it is based on localized spatial scale. In fact, there is no hierarchy of objects to traverse for the currently proposed algorithm. This is also true for other types of graphics, such as charts, for which an appropriate automatic zooming algorithm is less obvious.
4.1.3. PARTICIPANTS

For this preliminary study, a total of two visually impaired and two blind subjects participated in the study. The first participant was totally blind, acquiring vision loss at an early age; the second participant recently acquired vision loss and had low peripheral vision; the third participant was legally blind since birth and had a little light/shadow perception in one eye; and the fourth participant was totally blind since birth. None of the participants had neurological disorders. All participants had previous experience with tactile graphics, including raised line, thermoform and textured diagrams. They all were also familiar with the haptic computer interface device used in this study from previous participation in studies performed in the laboratory on the accuracy of length and angle perception with the device, and the previous zooming algorithm. All participants signed informed consent forms, and received payment for their participation. This study followed the tenets of the Declaration of Helsinki on Research Involving Human Subjects. It was approved by the VCU Institutional Review Board.

4.1.4. EXPERIMENTAL STIMULI

For this concept validation of our haptic zooming, four diagrams, containing line diagrams of simplified floor maps of two hospitals, were used. Each diagram also contained five universal symbols providing information about the rooms or areas on the map. The first two diagrams represented the first floor map of the buildings and contained
areas for information, a telephone, wheelchair access, an eye clinic and the stairs to the second floor (e.g., Figure 19a). Similarly the other two maps represented the second floors, containing areas for food, coffee, an orthopedics clinic, a hearing clinic and general medicine (e.g., Figure 19b). The positions of the symbols on all the diagrams were randomized and symbols were not repeated on the same map. To allow participants to become familiar with the haptic device and the type of diagram being presented a similar diagram, also containing universal symbols, was used for training purposes.

Figure 19. a) Shows one of the first floor maps and b) Shows one of the second floor maps of the hospital building.

4.1.5. EXPERIMENTAL PROCEDURE

For both the training and testing portions of the experiment, participants were required to use a blindfold so that only touch would be used to perceive the diagrams. They sat at a table and were presented with physical raised line diagrams (during training)
or the haptic device in front of them to be used to explore the diagrams. During training, each participant was first presented with physical raised line drawings of the universal symbols in order to familiarize themselves with them. Then they were trained how to explore the same symbols represented on the haptic display device, where each symbol was presented one at a time and covered the entire device workspace. The drawings were presented using the computer program developed, but the participants were not told how to zoom yet. Lastly, participants were trained on how to use the mouse buttons to zoom in and out on an area of the diagram, and the meaning of the auditory beeps. Training took approximately an hour.

During testing, two conditions were used to evaluate the effectiveness of using the zooming algorithm with the haptic device: (a) in one condition, zooming was allowed, and (b) in the other condition, zooming was not allowed. The conditions were presented in sequence to a participant, where the ordering was random and counterbalanced across participants. For each condition, participants received two maps, consisting of one of the two first floor maps and one of the two second floor maps, both randomly chosen and presented in random order. An experimental design where zooming/no zooming and first floor/second floor were both within-subject conditions was used.

For each map, the testing task was to (1) identify the position and (2) identify the name of the five symbols present on the map. For each map, the measured variables were: (1) the number of symbols for which the position were correctly identified, (2) the number of symbols identified correctly, (3) the time taken to identify individual symbols, which for each symbol was the difference between the time the user started exploring the symbol and
when they responded with an answer, (4) the overall time taken to complete the testing task for the diagram and (5) the number of times zooming was prevented from occurring when it provided no additional details.

At the end of the experiment, participants were asked to take the System Usability Scale (SUS) survey (Brooke, 1986): they were asked to respond on a Likert scale from 1 (strongly disagree) to 5 (strongly agree) to each question in the survey. The SUS score was recorded only at the end of the experiment and only for the zooming functionality. The SUS score was not recorded for the no zooming condition as it was suspected that participants would rate the use of the device rather than the lack of the zooming functionality.

4.2. RESULTS

We observed, not surprisingly that the participants used similar initial strategies to detect the position of the symbols in the maps when using the zooming or no zooming conditions. For both zooming conditions, three participants (S1, S3 and S4) used a random exploration strategy, where they kept moving the device unsystematically around the workspace until they felt something on the fingertips. In contrast, participant S2 moved the haptic device from left to right on the diagram to detect something at their fingertips. However, all four participants, in both conditions, used the same initial strategy to distinguish symbols from the walls of the building, namely, the closeness of lines to each other. If the lines were more densely spaced, it was assumed that a symbol was present.
When zooming was allowed, participants appeared to further use the zooming function for evidence (or lack thereof) of a symbol: a single, in contrast to a double, beep was used to determine that no symbols were present. In both conditions, we noticed that participants mostly confused the corners of the rooms with the symbols.

After a symbol was found, in the no zooming condition, participants directly started exploring a symbol by moving the haptic device over it: as shown in the identification results, performance was poor. In the zooming condition, participants used the mouse buttons to immediately zoom the symbol before they started to explore. Once zoomed on the symbol, participants (S1, S2 and S3) followed the lines of the symbol to identify it. However, participant S4 moved the device randomly over the space covered by the symbol to identify it. The latter difference may be why S4 performed more poorly on the symbol identification task (Figure 20b).

We found that for the first task of finding the position of the symbols on the diagram, participants without zooming were able to correctly identify the positions 92% (SD= 9%) of the time, whereas, with zooming, they correctly identified the positions 100% (SD=0%) of the time (Figure 20a). For the second task, participants were able to correctly identify only 20% (SD= 9%) of the symbols without zooming but 78% (SD= 13%) with zooming (Figure 20b). Participants also tried to zoom in on areas that zooming would provide no further details, but were prevented, an average of 7 times (SD= 3) per diagram using the zooming algorithm (Figure 20e). The response time per correctly identified symbol was found to be 40 sec (SD = 5sec) without zooming and 79 sec (SD=18 sec) with zooming (Figure 20c). Whereas, the over all response time was found to be on average, 2.5
times longer for the zooming condition (16 min) as compared to (6.5 min) without zooming (Figure 20d).

The system usability scale survey for our zooming technique gave a mean score of 67, with 0 being non usable and 100 most usable (Figure 20f). This was a moderately low score, we found that this was due to the low score ratings for two questions, (1) I would need the support of a technical person to be able to use the system and (2) I found the system cumbersome to use. But based on the qualitative feedback and observations, we found that users like the zooming capability and felt more confident in giving answers when using it.

However, we also observed that most of the participants had problems actually using the mouse buttons to perform the zooming function. Participants S3 and S4 had a difficulty in holding the haptic device still while searching for the mouse buttons on the device and using them. Sometimes, the haptic device moved far enough away from the symbol during this time that, when the appropriate buttons was pressed, no zooming occurred. We also noticed that most of the participants (S2, S3, S4) had a tendency to press the button for a relatively long time; this was occasionally registered as a double click by algorithm which performed double level zoom on the diagram. The unexpected extra zoom and the resulting addition beeps created confusion for the participants. One of the participants (S4), unfortunately got really upset with this problem: to prevent them from discontinuing the experiment, the experimenter volunteered to press the zooming button for the participant at the desired location when requested.
Figure 20. Results of a) symbol position identification task summed for both diagrams (out of 10), b) symbol identification task summed for both diagrams (out of 10), c) average symbol identification response time for both diagrams, d) over all response time summed across both diagrams, e) No-Zoom button click summed for both diagrams and f) system usability scale survey scores of the participants.

4.3. DISCUSSION

The main aim of this work was to perform a preliminary investigation to determine whether our ongoing development of a more effective haptic zooming technique was heading in a potentially beneficial direction. In particular, we wanted to examine the most basic question of whether our zooming technique improved performance of tasks that required processing of details of a diagram over the “standard” condition of using no zooming. We found that participants using our current zooming technique did improve their ability to determine symbols over the no zooming technique. As it was necessary to understand details to determine these symbols, it suggests that participants did take advantage of the zooming to interpret the details more effectively. For the average response time for interpreting a symbol, we found that participants, contrary to our expectations, took longer to determine a symbol using the zooming condition, which also resulted in a longer time taken. Unfortunately, we did not take detailed comments on these
results, but one possible explanation is that users “gave up” with the no zooming condition but, as the zooming condition was productive, spent a longer time acquiring information.

From the observations of the participants performing the experiment and the SUS responses, we also found areas that could be improved to obtain better performance and make the difficulty of performing the tasks easier. Observing the responses for individual questions of the SUS, we found that users found the system cumbersome and difficult to use independently. We believe that this was mainly due to the problem that longer button clicks, as used by our participants, sometimes resulted in double button clicks, which resulted in confusion by the participants as to what was happening. We will investigate two alternatives to address this problem, either by: (1) making the process of zooming into a two click process with separate buttons, which would also prevent zooming by accidental pressing of a button, or (2) providing more auditory feedback about the levels of zoom, such as indicating “Level 1”, “Level 2” and so on for every click instead of just the auditory beeps. Another problem that should be addressed is the accidental movement of the haptic device when trying to zoom failing in allowing a zoom. In future, we will explore whether increasing the size of the detail box might address this problem. Finally, as differences in performance between participants appeared to possible correlate with search strategies, more effective training methods may also improve performance and make the system easier to use during an actual task.

One of the major limitations in drawing strong conclusions from our study is the low number of participants. Another was the limitation of using only one specific type of diagram. Although these limitations exist, they were necessary for providing relatively
quick feedback on the direction of our development project. Unfortunately tactile graphics, particularly when accessed with haptic devices, are very time consuming to use. At this preliminary stage, we did not feel it would be productive to use more subjects and more types of diagrams. However, these issues will be further addressed in future studies. In addition, again to address time issues, a task that narrowly focused specifically on whether details can be used more effectively with our zooming technique (as opposed to no zooming) was proposed. In the future, a larger variety of questions that may explore less specific and/or more complex use of zooming will be considered.

Another limitation of the current study is that it could not confirm the hypothetical advantages, mentioned in the introduction, of the currently proposed zooming technique to other possible haptic zooming techniques. For example, the larger number of times users tried to zoom and were told that there was nothing there was potentially a time saving component of this algorithm. However, it can only be truly validated by comparison to an algorithm without this component. Two other aspects discussed in the introduction: (1) determining whether the number and “dynamic stepsizes” chosen saved time and effort, and (2) the avoidance of cropping improved performance, in comparison to other algorithms, could not be validated. Finally, maximizing the objects/sub-parts on the display is also expected to improve performance (Wijntjes et al., 2008) which occurs automatically with our algorithm but not others.

Finally, as mentioned in the algorithm section, this algorithm is expected to be primarily useful for pictures, system and device layouts, and building layouts. The key feature for the algorithm’s use is that the given diagram can be organized in terms of a
hierarchy of objects and sub-objects that can then be traversed in a tree like structure. However, it is expected that other types of diagrams will perform better with other types of zooming algorithms. The investigation of the type of diagram on the effectiveness of an algorithm also needs to be investigated. We suggest that using refreshable haptic display devices, combined with different computer techniques, such as the one presented in this study make it a powerful tool for interpreting graphical information. However, more thorough testing of our improved haptic zooming algorithm is warranted.

In future we would like to compare our proposed haptic zooming to more conventional techniques that have been used by others to verify its expected advantages for the diagram types proposed. We would also like to investigate the effect of diagram type on the performance of these algorithms. Finally, we are also interested in further examining other software techniques which will aid in the navigation of information, including the incorporation of “semantic zooming”, which would allow details to emerge only as the user zooms in. This would help avoid “clutter” at the higher levels of zoom, making it easier to interpret a graphic.
5. INTUITIVE TACTILE ZOOMING FOR GRAPHICS ACCESSED BY INDIVIDUALS WHO ARE BLIND OR VISUALLY IMPAIRED

In this chapter, we present the last study that was performed towards the first goal of the development of the automated magnification tool for AHUI. In a previous pilot study, we found that individuals who are blind or visually impaired appeared to prefer using zooming for exploring a detailed diagram compared to using no zooming, and they improved in the accuracy of their performance (Rastogi & Pawluk, 2012a). In this study we conducted a comprehensive experiment to evaluate the effectiveness of the proposed advantages of our intuitive zooming algorithm.

5.1. METHOD: COMPARISON OF ZOOMING TECHNIQUES

The main aim of this study was to compare our intuitive zooming technique with the more conventional techniques of using a linear and logarithmic step zoom. A variety of diagrams that would require multiple levels of zooming were used. Performance was assessed by determining the correctness of the answers to a set of questions and the amount of time it took to complete the questions.
5.1.1. PROPOSED ZOOMING APPLICATION

5.1.1.1. CONCEPT

In addition to the obvious concern about spatial resolution, our design of a zooming algorithm for raised line drawings was based on handling a significant limitation that is known to exist in haptics: namely that the processing of 2-D geometric information (which is the sole information in raised line drawings) is a slow and serial process (in contrast to vision which is quick and in parallel) (Lederman & Klatzky, 1990). This process is thought limited to a single finger even if multiple fingers may be available for use (Loomis et.al., 1991; Jansson & Monaci, 2003; Craig, 1985) (although see Klatkzy and colleagues (1993) for a somewhat contrary result). It is also most likely the reason for the difficulties in interpreting what the raised lines mean (e.g., exterior or interior boundaries of objects and parts, part of the 3-D perspective, or resulting in the occlusion of a part behind it). Together, this means that it may take some time before a user realizes that: (1) a zoom level is uninformative (e.g., too similar to the previous level), and (2) an object is actually clipped at the boundary of the display.

One potential solution we considered to avoid “uninformative” zoom levels was to judiciously select them manually in advance for each virtual environment or diagram as in (Schloerb et.al., 2010). Although this may be appropriate when using a single virtual
environment, it is potentially impossible (e.g., Schmitz & Ertl, 2010), to provide a single “optimum” set of levels which can be used with many different diagrams. We also wanted to avoid requiring the zoom levels to be selected manually for each diagram to minimize the amount of outside intervention needed for generating each diagram (ideally the whole diagram creation process would be automated). For handling clipping, we first considered using panning to solve this problem. However, it potentially suffers from the same problem as for zoom levels, in that many panning steps may be chosen before obtaining the desired results or the panning step may be so large and clip the object on the other side.

Our proposed solution is to automatically determine “intuitive” zoom levels for each raised line diagram based on navigating an object hierarchy of the picture. Using one of the child nodes to be the next zoom level, depending on the position selected, ensures that the next zoom level will be significantly different from the last. For example, for Figure 21b, three examples of automatic selection of “intuitive” zoom levels are shown by the dashed-dotted lines. The dashed-dotted lines in the diagrams (Figure 21 a,b,c) are for illustration purposes only and were not present on original diagram. Notice that clicking on different objects scales the zooming differently (e.g., Figure 21a cf. Figure 21e) so as to fit the local object maximally in the display area. This makes our solution very different than step zooming, which would have fixed steps of zoom independent of object size and constant for all areas of the diagram. Sizing the object to fit maximally into the display space is expected to: (1) avoid clipping and (2) improve performance over a smaller sized object (Wijntjes et.al., 2008). As this solution is object based, it is likely most appropriate
for such diagrams as those relating objects and object scenes, which will be the focus of our testing.

Figure 21. Example Diagram (b) and Subsequent Zoomed Areas (all other diagrams)

Another aspect of our zooming algorithm is that, in the local context of the diagram, objects that are close together (e.g., the house with an adjacent plant) are considered a meaningful cognitive component. The reasoning behind this is that a user may actually want to take a closer look at the relationship between adjacent objects (e.g., is there a flower or tree beside the house). This is likely to be less true for objects further from each other. This does not preclude examination of the individual objects (and their components) as this will happen at the next zoom level for that local area. For example, for the house and flower (Figure 21c), if a user then zooms within the area indicated by the dashed-dotted line, the flower will be shown individually (Figure 21f).
5.1.1.2. APPLICATION

The application starts with a raised line drawing containing all the intended detail in a single diagram (Figure 21b). The application then performs the pre-processing stage to automatically perform the steps necessary for creating an object/object group hierarchy (e.g., the tree hierarchy created for Figure 21 is shown in Figure 22). Then the tree hierarchy is traversed when the user clicks locally on an object/object group of the current diagram to appropriately zoom the relevant component.

![Diagram Hierarchy](image)

Figure 22. Diagram Hierarchy
The first step in developing the object/object group hierarchy was to use the Moore-Neighbor tracing algorithm modified by Jacob’s stopping criteria (Gonzalez and Woods, 2008) with an 8-connected neighborhood. This algorithm traces the exterior boundaries of object regions as well as holes inside the objects producing a tree hierarchy. However, as we use it to extract the object hierarchy for lines, it produces double boundaries for some lines and more complicated relationships for others (e.g., in Figure 23, boundary 14 may be considered redundant with boundary 3 and boundary 17).

The next step was to remove these “extraneous boundaries”. For this, the developed tree was traversed and children were removed from the tree (and replaced with their children) if: (1) they shared part of the parent boundary and (2) their path length was 75% of the parent boundary. It is noted that 75% was arbitrarily chosen and further
investigation, based on the perception of object parts in relation to the whole, is needed to choose a more appropriate value, and possibly a more appropriate metric.

The last step was to add object groups to the tree hierarchy based on their being meaningful cognitive components (e.g., for Figure 21b, the flower and the house can be considered a cognitively related group, as well as the flower head – petals and disk, lower in the given tree branch). To determine this, child nodes with the same parent were compared to each other: if the shortest distance between them was less than $1/8$ of the larger of the height and width, they were grouped together. Transitive laws were then used to combine groups. Then the new node was inserted between the parent and the relevant child nodes. It is noted that $1/8$ was arbitrarily chosen and further investigation, based on grouping by proximity laws, is needed to choose a more appropriate value.

To use the developed application, two buttons on the “mouse-like” display were used to zoom in and out, navigating down or up the tree, respectively (Figure 22). If the zoom-in button is clicked at a given node in the tree and (a) it has no child nodes or (b) it is not near the object/object group associated with any of the children (i.e., their bounding box), then no action occurs and the user is notified with a single auditory beep. Otherwise, if the object/object group of one or more children covers the position, the one with the closest centroid is selected for display. If instead the zoom-out button is clicked and there is no parent (i.e., it is the root node), then again, no action occurs and a single auditory beep occurs. Otherwise, the parent of the current node is selected for display.

To display the chosen node, a rectangular bounding box area of the virtual diagram corresponding to the selected child node is displayed centered and maximized in size based
on its scaling factor. However, lines other than those due to the child node and its
descendants are removed from the display to avoid presentation of incomplete objects
which may confuse the user. In addition, a double auditory beep is made to indicate that
zooming occurred.

5.1.2. PARTICIPANTS

A total of seventeen individuals (9 male and 8 female, mean age of 41.4 ± 11.5
years, 14 right handed and 3 left handed) who were either blind or visually impaired
participated in the experiment. Five participants were totally blind with no vision in both
eyes: one of which was congenitally blind, while the other four were adventitiously blind.
Of the adventitiously blind participants, one lost vision at age eight and the rest lost vision
within the last ten years. The remaining twelve participants were visually impaired: eight
had low vision (20/200 to 20/400) and the other four had limited vision (light/shadow
perception or low peripheral vision). One participant had neuropathy, but had enough
tactile sensation to perform the experiment. All participants except six were naïve to the
haptic device and never used it previously. Ten participants had never used any sort of
(visual) zooming before and three had never used computers. This study was approved by
the VCU Institutional Review Board (IRB).

5.1.3. EXPERIMENTAL SETUP
The haptic device shown in Figures 12 was used for the experiment. The device consists of a single refreshable electronic Braille cell, placed between four buttons of a hollow mouse case, providing tactile feedback to the user about local information displayed at a position of a virtual diagram. A hollow mouse case was chosen to hold the Braille cell to make it more ergonomical while maintaining a low cost. During use, the device is moved across a graphics tablet (Adesso 1200, Adesso Inc, 2011) to explore the virtual diagram. The position of the display is tracked through a RF transmitter placed directly underneath the Braille cell. The position is mapped onto the virtual diagram and the individual pins are either raised when on a line or lowered when on the background. For this application, the four buttons on the device were programmed to allow the user to: zoom-in, zoom-out, return to the original image (root node) and exit the program.

For our intuitive zooming technique, the method of zoom used is that described above. For the conventional step zooming techniques, methods that have been typically applied to visual zooming were used. For these methods, every zoom button “click” made the original image larger in linear or logarithmic steps, such that the position clicked on in the initial diagram becomes the center of the zoomed diagram. The zooming step increments allowed were: for linear step zooming, 1x, 2x, 3x, 4x, 5x, 6x, 7x, 8x, 9x; and for logarithmic step zooming, 1x, 2x, 4x, 8x, 16x, 32x, 64x, 128x.

5.1.4. EXPERIMENTAL STIMULI
To compare zooming techniques, diagrams containing objects with components of varying sizes were used. Questions were asked that required participants to make some of the objects larger using zooming. Two sets of diagrams (e.g., Figure 24) were used for testing: diagrams of villages or diagrams of lakes. For each zooming condition, 3 diagrams from a set of 9 were chosen randomly to minimize learning effect. Each testing diagram consisted of six objects of a similar type but varying in size and placed at different positions of the diagram. For the village diagrams (Figure 24a), each house always had: a roof, two windows, a door (with a round knob) or no door, a flower pot and a flower with petals. Similarly for the lake diagrams (Figure 24b), each boat had: an engine, either on the left or right side, a mast with flags and a helm with handles. These features were chosen at random for individual objects of a diagram. Diagrams with different objects from the testing sets were used for training: three diagrams (e.g., Figure 25) containing four to six objects, such as pine and deciduous trees, cars and trucks and a cat were created.
Figure 24. Example of pseudo-randomly generated testing diagrams used for comparing the zooming techniques; a) village diagram and b) lake diagram.
5.1.5. EXPERIMENTAL PROCEDURE

The experiment was divided into two sessions, one a day. On day one, participants were trained on using the device and then trained and tested on one of the zooming techniques. On day two, participants were trained and tested on the two other zooming techniques, one at a time. Both days, sessions lasted approximately 3-4 hours. The order of using the three techniques (linear, logarithmic and intuitive) was counterbalanced across participants. One diagram from each set of diagrams (training set, house set and boat set) was also selected for each technique, counterbalanced across participants; the latter chosen to be uncorrelated with the counterbalancing across techniques and the diagrams chosen from the other sets. Finally, during testing, the village diagram and the lake diagram were presented in random order.
At the beginning of the first session, participants were given instructions about the experiment followed by training to familiarize them with the device. This training included freely exploring diagrams of familiar shapes (e.g. a square or circle) using the device. Later, participants were given training on transitioning from raised line drawings (which they were familiar with) to virtual diagrams using the device; for this they were first presented with raised line drawings of a house and a boat, followed by presenting the same diagrams using the device. This initial training session lasted about 35-45 minutes.

Once comfortable using the device, participants began the testing component of the experiment. For each zooming technique, participants were first trained on how to use it, then asked to answer questions pertaining to the two test diagrams and, finally, asked to take the System Usability Scale Survey (Brook, 1986). Training was performed on a training diagram. This included explicitly explaining to the participant that for the intuitive zooming the object zoomed on would be centered in the new diagram shown, and that for the step zooming the position on the virtual diagram which was clicked on would be centered in the new diagram shown. Training continued until the participant could use the mouse buttons correctly, and understand the zooming and the auditory feedback (beeps) without assistance by the experimenter.

Both a village diagram and the lake diagram were used during testing. Participants had to first locate each object on a diagram and then answer five questions about it (for a total of 30 questions per diagram). Answers to the questions were recorded, as well as the response time and number of clicks, on a per object basis (each of which had 5 related questions). The questions asked are given in Table 1. For the System Usability Scale
Survey, participants were asked to respond to the statements in Table 5 on a Likert scale from 1 (strongly disagree) to 5 (strongly agree). They were also asked to give comments about the zooming techniques that were not covered in the survey.

### Table 1

Questions asked and their response per object on the two testing diagrams.

<table>
<thead>
<tr>
<th>Image</th>
<th>Questions</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Village</td>
<td>What type of roof does the house have?</td>
<td>Conical / Flat</td>
</tr>
<tr>
<td>Diagram</td>
<td>How are the windows oriented?</td>
<td>above each other/ side by side</td>
</tr>
<tr>
<td></td>
<td>Is there a door in the house?</td>
<td>yes (round knob) / no</td>
</tr>
<tr>
<td></td>
<td>Which side of house is the plant?</td>
<td>left / right</td>
</tr>
<tr>
<td></td>
<td>How many petals are there on the flower?</td>
<td>three / four</td>
</tr>
<tr>
<td>Lake</td>
<td>Which side is the engine connected?</td>
<td>left / right</td>
</tr>
<tr>
<td>Diagram</td>
<td>What type if engine is it?</td>
<td>propeller (spoke) / paddle (circular)</td>
</tr>
<tr>
<td></td>
<td>How many flags are there on mast?</td>
<td>one / two</td>
</tr>
<tr>
<td></td>
<td>Which direction are they pointed?</td>
<td>left / right</td>
</tr>
<tr>
<td></td>
<td>How many handles on the helm?</td>
<td>two / three</td>
</tr>
</tbody>
</table>
5.1.6. **STATISTICAL METHOD**

For comparing the performance of the developed intuitive zooming technique to linear and logarithmic zooming, three response variables were considered: the percentage of correct responses per object, the response time per object, and the number of clicks per object. Generalized linear mixed models (GLMM, Molenberghs & Verbeke, 2006) were chosen to model these response variables. The models for all variables included effects for technique (intuitive, linear, logarithmic), diagram set (village, lake), diagram number (1, 2, 3) nested within diagram set, object number nested within diagram set and diagram number, and the technique by diagram set interaction. Initially, a test of the technique by diagram set interaction effect was conducted to determine if performance depended on the diagram set used. If this effect was significant ($p$-value < 0.05) then the effect of technique depends on diagram set, and consequently the effect of technique were tested separately for the two diagram sets. If the interaction effect was not significant ($p$-value > 0.05) then the effect of technique was consistent across the diagram sets, and the effect of technique was tested irrespective of diagram set. To examine the participants’ satisfaction with the different techniques, the overall scores for the system usability scale survey (SUS) for the three methods were determined according to the method described by Brooke (1986). The overall scores were then compared between groups using matched pair $t$-tests.

5.2. **RESULTS**
A GLMM was used to model the percentage of correct responses per object assuming a binomial distribution for the response variable and a logit link function. The estimated percentage of correct responses produced by the model for each technique, overall (Figure 26) and by diagram set, is summarized in Table 2. There was no evidence of a significant technique by diagram set interaction effect \((F(2, 572) = 0.05, p\text{-value} = 0.95)\), thus this effect was removed from the model. The results from the resulting model showed there was evidence of a significant technique effect, thus there were significant differences in the percentage of correct responses by the three different zooming techniques \((F(2, 30.3) = 43.9, p\text{-value} < 0.001)\). When comparing the logarithmic and linear techniques, the odds of having a correct response did not differ in a significant manner \((\text{odds ratio} = 1.14:1, 95\% \text{ CI} = 0.93, 1.40)\). However, there was a significant increase in the odds of having a correct response for our intuitive zooming technique as compared to that for the logarithmic (131\%) and linear (164\%) techniques; these corresponded to odds ratios of 2.31:1 \((95\% \text{ CI} = 1.85, 2.89)\) and 2.64:1 \((95\% \text{ CI} = 2.11, 3.29)\) respectively. Thus, using intuitive zooming resulted in a great improvement in the number of correct responses compared to the other techniques, which performed similar to each other.
Table 2

Estimated Percentage of Correct Responses by the Model per Object for the Zooming Techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Probability Correct</th>
<th>Probability Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate (SE)</td>
<td>95% CI</td>
</tr>
<tr>
<td>Linear</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>61.15 (2.64)</td>
<td>(55.60, 66.41)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>61.08 (3.06)</td>
<td>(54.78, 67.03)</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>64.27 (2.26)</td>
<td>(58.85, 69.35)</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63.75 (2.99)</td>
<td>(57.54, 69.54)</td>
</tr>
<tr>
<td>Intuitive</td>
<td>80.59 (1.88)</td>
<td>(76.49, 84.13)</td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80.03 (2.28)</td>
<td>(75.09, 84.20)</td>
</tr>
</tbody>
</table>

*SE = Standard Error, CI = Confidence Interval
5.2.2. RESPONSE TIME PER OBJECT

A GLMM was used to model the response time per object assuming a Poisson distribution for the response variable and a log link function. The estimated response time per object (in minutes) produced by the model for each technique, overall (Figure 27) and by diagram set, is summarized in Table 3. As there was evidence of a significant technique by diagram set interaction effect ($F(2, 572) = 4.33, p$-value < 0.001), the effect of zooming technique was examined separately for the two diagram sets (Village and Lake). However, there was not a significant difference between the zooming techniques on response time for
either the Village \((F(2, 36.8) = 0.29, \ p\text{-value} = 0.75)\) or Lake \((F(2, 39.4) = 2.32, \ p\text{-value} = 0.11)\) sets.

Table 3
Response Time by the Model per Object for the Zooming Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Response Time in minutes</th>
<th>Diagram</th>
<th>Response Time in minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate (SE)</td>
<td>95% CI</td>
<td>Estimate (SE)</td>
</tr>
<tr>
<td>Linear</td>
<td>5.57 (0.55)</td>
<td>(4.56, 6.81)</td>
<td>Village 5.65 (0.58)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lake 5.50 (0.57)</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>5.85 (0.58)</td>
<td>(4.79, 7.15)</td>
<td>Village 6.16 (0.63)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lake 5.56 (0.57)</td>
</tr>
<tr>
<td>Intuitive</td>
<td>5.08 (0.50)</td>
<td>(4.16, 6.21)</td>
<td>Village 5.81 (0.60)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lake 4.44 (0.47)</td>
</tr>
</tbody>
</table>

*SE = Standard Error, CI = Confidence Interval
5.2.3. NUMBER OF ZOOMING CLICKS PER OBJECT

A GLMM was used to model the number of zooming clicks per object assuming a normal distribution and an identity link function. The estimated number of zooms for each technique produced by the model, overall (Figure 28) and by diagram set, is summarized in Table 4. There was no evidence of a significant technique by diagram set interaction effect ($F(2, 46) = 0.97, p$-value $= 0.39$), thus this effect was removed from the model. The results for the actual model revealed evidence of a significant technique effect ($F(2, 30) = 141.6, p$-value $< 0.001$). Participants with the logarithmic zooming technique were found to use significantly fewer zooms than the linear technique (difference $= 1.97, CI = 1.58, 2.37$). The intuitive zooming technique performed significantly better than both the linear and the
logarithmic zooms with a decrease in the number of zooms used of 3.25 (95% CI = 2.84, 3.64) and logarithmic 1.27 (95% CI = 0.87, 1.66) respectively. Thus, performance was noticeably better, in terms of minimizing zooming clicks, for the intuitive zooming technique, followed by the logarithmic and then the linear technique.

Table 4

Number of Zooming Clicks by the Model per Object for the Zooming Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Estimate (SE)</th>
<th>95% CI</th>
<th>Diagram</th>
<th>Estimate (SE)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>5.54 (0.18)</td>
<td>(5.17, 5.88)</td>
<td>Valley</td>
<td>5.41 (0.21)</td>
<td>(4.99, 5.53)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lake</td>
<td>5.64 (0.21)</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>3.55 (0.18)</td>
<td>(3.19, 3.90)</td>
<td>Valley</td>
<td>3.63 (0.21)</td>
<td>(3.21, 4.05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lake</td>
<td>3.47 (0.21)</td>
</tr>
<tr>
<td>Intuitive</td>
<td>2.28 (0.18)</td>
<td>(1.93, 2.64)</td>
<td>Valley</td>
<td>2.38 (0.21)</td>
<td>(1.96, 2.80)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lake</td>
<td>2.19 (0.21)</td>
</tr>
</tbody>
</table>

*SE = Standard Error, CI = Confidence Interval
5.2.4. SYSTEM USABILITY SCALE SURVEY

The average responses for individual statements are given in Table 5. The overall scores for the system usability scale survey (SUS) for the three methods (Figure 29) are summarized in Table 6. Matched paired t tests (df = 16) on the data revealed that intuitive zooming had a significantly higher score as compared to both linear (p=0.0001, difference =36.03, SE= 5.48) and logarithmic scores (p=0.0002, difference = 19.26, SE=4.08) and the logarithmic technique had significantly higher average scores than the linear technique (p=0.019, difference = 16.76, SE=6.45).
Table 5

System usability scale survey averaged responses for the individual zooming techniques.

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Statement</th>
<th>Average of Subjects Ratings*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>1</td>
<td>I think that I would like to use this system frequently</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>I found the system unnecessarily complex</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>I thought the system was easy to use</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>I think I would need the support of a technical person to be able to use this system</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>I found the various functions in this system very well integrated</td>
<td>3.4</td>
</tr>
<tr>
<td>6</td>
<td>I thought there was too much inconsistency in this system</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>I would imagine that most people would learn to use the system very quickly</td>
<td>2.9</td>
</tr>
<tr>
<td>8</td>
<td>I found the system very cumbersome to use</td>
<td>3.8</td>
</tr>
<tr>
<td>9</td>
<td>I felt very confident using the system</td>
<td>3.2</td>
</tr>
<tr>
<td>10</td>
<td>I needed to learn a lot of things before I could get going with the system</td>
<td>2.8</td>
</tr>
</tbody>
</table>

*1 (strongly disagree) to 5 (strongly agree) ** higher rating of statements (1,3,5,7,9) and lower rating of even statements (2,4,6,8,10) shows increased usability
Table 6
System Usability Scale Survey

<table>
<thead>
<tr>
<th>Technique</th>
<th>Overall Ratings</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE)</td>
<td>95% CI</td>
</tr>
<tr>
<td>Linear</td>
<td>48.82 (5.43)</td>
<td>(37.32, 60.33)</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>65.59 (4.36)</td>
<td>(56.35, 74.83)</td>
</tr>
<tr>
<td>Intuitive</td>
<td>84.85 (3.70)</td>
<td>(77.00, 92.70)</td>
</tr>
</tbody>
</table>

*SE = Standard Error, CI = Confidence Interval

Figure 29. System usability scale survey results for the testing techniques.

5.3. SUBJECTIVE COMMENTS
After the experiment, we asked participants if they had any comments about using the different zooming techniques to which several participants responded. When asked for general feedback about the intuitive zooming technique, most comments referred to three main features: participants very much liked: (1) the prevention of zooming if no further information could be obtained (P5, P8, P10, P11, P14, P15), (2) having the zooming being object-based, which also resulted in the removal of other objects from the display when zooming to size (P12), and (3) having the objects enlarged to the full display size on zooming (P8, P10, P12, P14, P15). Some (direct, not paraphrased) comments from participants included: P14, “I can click anywhere and know if the object is on the screen or not”; P10, “It’s really neat, being able to zoom on one particular part was very helpful”; P12, “It was great that objects get removed and become large”; and P15, “Love this technique, as everything became large in one click”. No participants expressed frustration or confusion with the intuitive technique.

In contrast, when participants were asked about the step zooming techniques (both linear and logarithmic), most of the comments expressed frustration and confusion (P10, P11, P12 for logarithmic and P14, P15 for linear)). In particular, these comments mentioned that the participant had problems with locating the objects on the display when they clicked on a position to zoom in on (despite training). Some (direct, not paraphrased) comments for these methods were: P10, “very difficult to use, takes a long time to find the image after zooming”; P15, “looking for objects after zooming was very difficult”; and P12, “confusing and difficult to use”. No one mentioned that they liked either of the step
zooming techniques. It is acknowledged that if different questions were asked some or all of these results could be different, however, the SUS survey was meant to address similar questions in a more objective manner.

5.4. DISCUSSION

The particular issue examined in this paper was how to effectively provide a zooming method to allow access to those details on a diagram which, although easily interpreted by vision, may be difficult to determine by touch. We believe that one concern is that the haptic processing of 2-D geometric information (i.e., which is the sole information provided by raised line drawings) is a slow and serial process (Lederman and Klatzky, 1990). This means that haptics may take some time, in contrast to vision, before a user realizes that a zoom level is uninformative or that an object presented is clipped at the boundary. Our proposed solution, particularly oriented to managing pictures of objects and object scenes, is to base the zoom levels on navigating an object hierarchy of the picture, to increase the likelihood that new information is always presented, and sizing the object/sub-object to maximally fit the display space. The latter is done not only to avoid clipping of objects but to improve performance over perception of a smaller version of the object (Wijntjes et al., 2008).

The performance of the developed, intuitive zooming technique was then compared to more conventional techniques (linear and logarithmic step zooming). We found, at least
for our particular diagrams and tasks, that intuitive zooming performed significantly better than the step zooming techniques that were implemented, with the odds of answering correctly increasing by approximately 150%. Admittedly, there was no significant difference in the response time, which we thought would decrease. However, considered together with the increase in correct answers for the intuitive zooming technique, it may indicate that more of the response time for the intuitive technique was spent exploring objects (resulting in more correct answers) than traversing the zoom levels. This was also supported by the result that fewer zooming clicks were used for intuitive zooming than the other types of zooming. Finally, no difference in performance was found between the linear and logarithmic zooming conditions in terms of the number of correct responses or response times.

The usability of the developed, intuitive zooming technique was also compared to the step zooming techniques. For the System Usability Scale Survey, the intuitive zooming technique had an increase in perceived usability of 74% compared to the linear step zooming technique and 29% compared to the logarithmic zooming techniques. This was also supported by the subjective comments given by the participants. The logarithmic zooming was also found to be significantly more usable than the linear zooming (an increase of 34%), although the subjective comments by participants were neutral.

5.4.1. DESIGN ISSUES
One potential issue that could have affected our results is that, although typically a zooming interface is coupled with panning, we considered zooming in isolation at this proof of concept stage. This possibly negatively affected performance with the step zooming techniques in that clipped objects could not be “simply panned” to the desired position: one would have to zoom out, move and zoom back in to obtain the same effect. However, haptic panning may suffer from the same potential limitation as zooming: when panning, many uninteresting steps may need to be explored haptically (which would be slow) before the object is centered or, if the panning step is too large, the object may be clipped at another border. Thus, there may not be a time advantage (and panning, itself, may benefit from a comparable “intuitive” algorithm).

Another related issue in the design, for the step zooming techniques, was that we chose the position clicked on in the virtual diagram to be the center of the zoomed diagram. This required that the participants be able to make the transposition from one zooming level diagram to the next. An alternative, such as in [21], maintained the position constant, which would make the relationship simpler. However, we thought this would greatly increase the chances of objects being clipped when zoomed and produce an unfair comparison.

Finally, the design for the intuitive zooming method contains two arbitrary parameters that could have affected performance: (a) the fraction of the path length at which a child boundary is decided to be the same as the parent (75%), and (b) the fraction of the height/width for determining the distance at which two compared boundaries are considered a “cognitive group” (1/8th). In future, perceptual experiments relating to (a)
how object parts are related to the whole, and (b) the Gestalt law of proximity may be effective in providing some evidence based values.

5.4.2. EXPERIMENTAL LIMITATIONS

One of the experimental limitations of our study is the small number of diagrams and their relative simplicity. These were chosen in order to make the experimental study tractable for this initial proof of concept stage, as more complex diagrams require much longer times to understand. It is possible that more complex diagrams with more connections between elements may produce different results. One particular diagram which may perform better with the other zooming methods are road maps, which may not be able to be broken down into zoom levels by our method, which is particularly oriented to managing pictures of objects and object scenes.

Another limitation was in the design of the questions. Unintentionally, the questions asked were focused on single branches of the object tree. It is possible that different results may be obtained when asking questions which span different branches of the tree, particularly at lower levels of each branch (such as where is the house with address 100 in relation to the house with address 200). Another type of question that may be difficult to answer with the current version of the intuitive zooming technique is the relative size of objects, as different amounts of zooming can occur for different objects in the diagram. However, this limitation may potentially be overcome by providing auditory feedback on how much each zoom level magnifies an object.
5.5. **FUTURE WORK**

The use of our intuitive zooming technique shows promise in improving access to raised line diagrams to individuals who are blind and visually impaired. However, more extensive work needs to be performed to investigate its performance with a wider variety of diagrams, with different degrees of complexity and with a variety of questions that describe relations both within branches of the object tree and between branches of the object tree. Also, panning needs to be considered as it is normally coupled with zooming and could be of benefit. A variety of methods for panning are possible and their performance both alone and together with zooming need to be evaluated. We propose to investigate an “intuitive” panning technique with “meaningful panning steps” based on the bounding box for each individual object/sub-object.
6. DYNAMIC TACTILE DIAGRAM SIMPLIFICATION ON REFRESHABLE DISPLAYS

In this chapter, we present the first study that was conducted towards the development of the automated simplification tool for AHUI. In this preliminary study, we investigated the potential utility of the two types of simplification mentioned on diagram interpretation. We hypothesized that depending on the type of question (i.e., general shape for boundary simplification and relational operators for context simplification), there will be an improvement in the accuracy of the response, a decrease in the response time, a reduction in the perceived difficulty and an increase in confidence in a participant’s answers. To test our hypothesis two experiments were conducted; Experiment 1 examines the effectiveness of boundary simplification to answer general questions about a geographical map and Experiment 2 examines the effectiveness of contextual simplification to answer relational questions of a geographical map.

6.1. EXPERIMENT 1: BOUNDARY SIMPLIFICATION

The intent of this experiment was to determine if the use of boundary simplification compared to using the original diagram with no simplification: (1) improves the accuracy
of the response to questions about the general shape of a country and the number of states, (2) reduces the amount of time needed to answer these questions, (3) reduces the perceived difficulty of these questions, and (4) increases user’s confidence in answering the questions. As this preliminary experiment was to investigate whether boundary simplification had any potential to be useful before further exploration of different algorithms and implementations, a single type of boundary simplification was used and was performed manually. Motivated by pilot testing, which found that users more easily tracked straight lines than other types of lines, a polygonal approximation was used for boundary simplification.

6.1.1. PARTICIPANTS

A total of eight individuals, as described in Table 7, participated in the experiment. Subject 4 mentioned that her vision (20/1000) was tested 6 months before and her vision has gotten worst since then. Many of the participants had previous experience with the device being used for this study, but not with the software algorithms. All participants received payment for their participation in the study. This study was approved by the VCU Institution Review Board and followed the tenets of the declaration of Helsinki on research involving human subjects.
Table 7
Details about the blind and visually impaired participant.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age</th>
<th>Sex</th>
<th>Vision*</th>
<th>Vision Loss</th>
<th>Dominant Hand</th>
<th>Device Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>Male</td>
<td>Totally blind</td>
<td>Age 8 years.</td>
<td>Left</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>Male</td>
<td>20/2400</td>
<td>Congenital</td>
<td>Right</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>Male</td>
<td>Low vision</td>
<td>Congenital</td>
<td>Right</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>Female</td>
<td>20/1000</td>
<td>Congenital</td>
<td>Right</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>Male</td>
<td>Low peripheral Vision</td>
<td>Congenital</td>
<td>Both</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>43</td>
<td>Female</td>
<td>Totally blind</td>
<td>Congenital</td>
<td>Right</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>Male</td>
<td>20/800 (L); 20/600 (R)</td>
<td>Congenital</td>
<td>Left</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
<td>Male</td>
<td>20/800 (L); no vision (R)</td>
<td>Congenital</td>
<td>Right</td>
<td>No</td>
</tr>
</tbody>
</table>

* L=Left Eye, R=Right Eye.

6.1.2. EXPERIMENTAL DEVICE AND SETUP

The haptic device used (Figure 12) consisted of a refreshable electronic braille cell (Metec, AG, 2010) mounted in a mouse case, which communicated the position of the center of the display to a graphics tablet (Adesso Inc, 2011) with a location transmitter.
inside the case (Owen et al., 2009). The refreshable Braille cell consisted of eight pins that can be individually raised, lowered or vibrated to produce tactile sensations. The mouse case also had 4 buttons, which could be individually programmed to perform user defined functions: for this experiment, all buttons were disabled.

6.1.3. EXPERIMENTAL STIMULI

Two sets of diagrams were made for the experiment. The first set consisted of five line diagrams each representing a hypothetical map of a country (e.g., Figure 30a) that contained two to four states (real countries were not used to avoid any effect of prior knowledge). The other set consisted of the same five line diagrams with the lines simplified to be represented by straight lines (e.g., Figure 30b). The overall shapes of the countries were chosen so that they could be easily described in relation to common objects, alphabet letters or numbers. To increase the perception of borders and distinguish the outer boundary (describing the country) from the inner boundaries (dividing the states), the border lines were made to vibrate at 70 Hz and 25 Hz respectively. A simplified training diagram using rectangles (such as in Figure 32a), was used to teach the participants how to explore the diagrams, and the difference between the two types of borders.
6.1.4. EXPERIMENTAL PROCEDURE

All participants were first given a verbal explanation about the experiment, and instructions about the task and the training session. The participants were blindfolded
during the experiment using a sleep shade. The experimental device was placed right in
front of the participant on a table at a comfortable height. The training diagram was used
for training: first to distinguish the two different vibrating borders, and then on how to
trace the boundaries. The training session lasted an average of 16 (SD=5) minutes.

During the testing session, the participants were presented with the 10 testing
diagrams (5 simplified, 5 unsimplified) in random order. For each diagram participants
were asked at the onset of the trail to: 1) describe the shape of the country, relating it to any
everyday object, alphabet letter or numerical digit and, 2) determine the number of states in
the country. The total response time to answer the two questions was recorded. After the
completion of the testing phase for each diagram, participants were asked to rate the
difficulty of the tasks and their confidence in their answer on a likert scale from 1(very
easy/confident) to 5(very difficult/not confident).

### 6.1.5. EXPERIMENTAL DESIGN AND ANALYSIS

For this experiment two testing conditions (5 diagrams each) were considered; (1)
the total number of correctly identified shapes (out of 5) and (2) correctly numbered states
for each country (out of 5) were recorded. The analysis for these response variables were
performed on the count data with subject as a within design factor. The response time,
difficulty and lack of confidence were recorded individually for all 5 trials of a condition
and then averaged. The main analysis was performed on these averages with subject as a
within design factor.
For the two sets of count data (overall geometry and number of states), the odds ratio was first calculated to provide some overall indication of improvement; where the odds ratio is calculated from:

\[ \text{odds ratio} = \frac{\text{number correct}_{\text{no simplification}}}{\text{number wrong}_{\text{no simplification}}} \times \frac{\text{number wrong}_{\text{simplification}}}{\text{number correct}_{\text{simplification}}} \]

The normalcy of the data was then examined. If the data looked reasonably normal, a within subjects repeated measures general linearized model (GLM) was used on the count data to test for significance. If the data was not normal, the related-samples Wilcoxon Signed Ranks Test (a non-parametric test) was used. For the remaining data (average time taken, average difficulty and average lack of confidence), the difference in the means was calculated to provide some overall indication of improvement. If the data was normal, a repeated measures GLM was performed, otherwise a related-samples Wilcoxon Signed Ranks Test (RSWSRT) was performed.

### 6.1.6. RESULTS AND DISCUSSION

For the first task of identifying the overall shape of a country, all participants used a search and tracking strategy: each participant moved the device until they found a border (search), then they followed the contour of the border with the device (track). Two participants (P1 and P6) always started their initial exploration at the bottom right corner, whereas all others started at random positions from trial to trial. For the second task, we observed that four participants (P2, P5, P7 and P8) used a horizontal sweep strategy to find
the state borders, where they moved the device from left to right starting at the top of the diagram and moving to the bottom. The other four participants (P1, P3, P4 and P6) used a random exploration task.

In terms of the effects of implementation on usage by participants: all participants used the device in their dominant hand except for P5. P5 used two hands, the right one for holding the device and the left index finger to read the Braille cell. When asked why he used this configuration, he replied that it was the way he reads Braille and found it more comfortable. In terms of the vibration stimuli, only one participant (P6) complained about the two vibrations not being tactually distinct. During the experiment, instead of changing the vibration stimuli, the experimenter stated the type of border when asked by the participant. None of the other participants had any problems distinguishing the two vibrating stimuli and liked them. However, one future possibility is to allow the user to set the vibrations to make them tactually distinct for them; alternately, automatic verbal feedback could be given to indicate what type of border.

In examining the response variables, the odds of correctly identifying the general shape of a country greatly increased with simplification by a factor of 538% (i.e., an odds ratio of 6.38). Using a RSWSRT (as the data was not normally distributed), it was found that this difference was significant (p=0.01). The odds of correctly identifying the number of states increased with simplification by a factor of 50% (i.e., an odds ratio of 1.50). However, using a RSWSRT (as the data was also not normal), it was found that this difference was not significant (p = 0.157). The differing results for the two questions are likely due to the differences in exploration strategies exhibited by the users as described
above. Only the first question clearly involved tracing boundaries, for which we expected boundary simplification to be useful. These results appeared correlated with the observation that participants found that they got lost more easily tracking lines that were not straight. This was also directly supported by one participant’s comments that he liked the images with straight lines as they were easier to explore. In contrast, the question in regards to the number of states, in retrospect, was not very good at ascertaining the usefulness of boundary simplification as no contour tracing was involved.

The time taken to perform the tasks was only marginally quicker for the simplified diagram than for the original diagram (with a difference of 68.3 seconds). Using a RSWSRT (as the data was not normal), which was not significant (p=0.263). This was actually quite surprising when considering that participants stated they got lost more easily tracking lines that were not straight. The lack of difference may be because participants “gave up” more easily with the non-simplified diagrams, although they made not queried on this issue.

The difference in the difficulty ratings of performing the task was only marginally better (0.53) for the simplified condition versus the original map. However, using a RSWSRT (as the data was not normal) it was found significant (p=0.017). Similarity for the lack of confidence ratings in performing the task was only marginally (0.65) better for the simplified condition versus the original map, but was significant (p=0.011). Although the differences were significant, the small differences suggest that better implementations and/or training methods should be investigated to ease the burden on the user.
Table 8.

Shows the results of the testing response variables for Experiment 1.

<table>
<thead>
<tr>
<th>Response Variables</th>
<th>Original</th>
<th>Simplified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE*)</td>
<td>%Correct</td>
</tr>
<tr>
<td>Shape Identification</td>
<td>2.13 (0.08)</td>
<td>42.6%</td>
</tr>
<tr>
<td>Number of States</td>
<td>2.00 (0.12)</td>
<td>40%</td>
</tr>
<tr>
<td>Response time (all 2 Qs)</td>
<td>520 (23) sec</td>
<td></td>
</tr>
<tr>
<td>Difficulty</td>
<td>3.18 (0.04)</td>
<td></td>
</tr>
<tr>
<td>Lack of Confidence</td>
<td>3.2 (0.06)</td>
<td></td>
</tr>
</tbody>
</table>

*SE = Standard Error Mean

6.2. EXPERIMENT 2: CONTEXTUAL SIMPLIFICATION

The intent of this experiment was to determine if the use of contextual simplification: improves the accuracy of the responses to questions relating features of a geographical map, reduces the amount of time needed to respond, increases the user’s confidence in the responses and reduces the perceived degree of difficulty of the questions, as compared to using the original graphic. Users were asked to make queries during active use of a graphic related to one type of feature or a combination of two types of features. In the case of the contextually simplified graphic, only features requested by the participant remained on the diagram. As this preliminary experiment was to examine if
contextual simplification is potentially useful, the association of a feature with a feature type was performed manually.

6.2.1. PARTICIPANTS

The same participants were used as in Experiment 1.

6.2.2. EXPERIMENTAL DEVICE

The same haptic device was used as in Experiment 1. The programmable mouse buttons were used to perform different actions. The button on the top-left was programmed to select the feature types to be displayed in contextual simplification. The button on the top right displayed the previous feature type. The button on the back right displayed the original image, with all the features types on it. The button on the back left closed the program.

6.2.3. EXPERIMENTAL STIMULI

Participants were tested with 2 diagrams. Each diagram (e.g., Figure 31a) represented a hypothetical country (real countries were not used to avoid any effects of a priori knowledge) consisting of 4 types of features: (1) boundaries (country and state), (2) physical features (water bodies, mountains and forest), (3) political features (cities and
roads) and (4) industrial features (coal mines and oil fields). The diagram was either presented with all features on it (the original diagram) or the user was allowed to select one or none of the feature types to show together with the boundary features (simplified diagram). As in experiment 1, country borders were made to vibrate at 70 Hz and state borders at 25 Hz. To increase the saliency and differentiation of the different features, they were represented by tactile animations (Figure 31b), which would occur repeatedly while the user was within a feature. A legend on each diagram, only covering those features presented, was used to provide auditory feedback about the meaning of each of the animations.

![Figure 31](image)

Figure 31. (a) Testing diagram consisting of all the features (b) Animation patterns of the Braille cells for the features used.

Two training diagrams were developed. The first diagram (Figure 32a) was a very simple diagram with a legend. The second diagram (Figure 32b) was a portion of a map for a third hypothetical country and included the legend. Figure 32c, shows the description of the levels of gray used and the corresponding feature type in the diagram.
6.2.4. EXPERIMENTAL PROCEDURE

All participants were first given a verbal explanation about the experiment, and instructions about the task and the training session. The participants were blindfolded during the experiment using a sleep shade. The experimental haptic device was placed right in front of the participant on a table at a comfortable height. Participants were first taught the six animation patterns and their corresponding feature until they were able to identify all the animations when asked at random. This training session lasted, on average, 8 (SD=2) minutes. Participants were then presented with the diagram in Figure 33a to distinguish the two different vibrating borders, learn how to trace the borders, search for features in the diagram and estimate the size of the features. This training session lasted, on average, 15 (SD=6) minutes. Finally, Figure 33b was used to train participants on how to use the mouse buttons to select the particular context simplification. This session on an average of 16 (SD=2) minutes.
During the testing phase, participants were presented with two testing diagrams in random order and randomly chosen to be with or without simplification in a balanced design. For each diagram 10 questions were asked (Table 9). The questions were all given at the beginning of the exploration process and repeated when requested by the participants. Participants were allowed to change their responses during the testing session. The time taken to respond to all questions was recorded. After the completion of the testing phase for each diagram, participants were asked to rate the difficulty of the tasks and their lack of confidence in their answer on a Likert scale from 1 (very easy/confident) to 5 (very difficult/not confident). At the end of the experiment, a systems usability scale (SUS) survey (Brooke, 1986) was performed, where participants were asked to rate the statements in the survey on a Likert scale from 1 (strongly disagree) to 5 (strongly agree) for both the testing conditions.
Table 9

Questions asked for each diagram to test the response variables.

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Determine the number of states in the diagram?</td>
</tr>
<tr>
<td>2</td>
<td>Identify the state with the largest forest range?</td>
</tr>
<tr>
<td>3</td>
<td>Identify the state with the largest lake?</td>
</tr>
<tr>
<td>4</td>
<td>Identify the state with the largest mountain range?</td>
</tr>
<tr>
<td>5</td>
<td>Identify the state with the maximum number of cities?</td>
</tr>
<tr>
<td>6</td>
<td>Identify the state with largest number of coal fields?</td>
</tr>
<tr>
<td>7</td>
<td>Identify the state with an oil field?</td>
</tr>
<tr>
<td>8</td>
<td>Identify the state with the city on the coast?</td>
</tr>
<tr>
<td>9</td>
<td>Determine the natural resources on the island?*</td>
</tr>
<tr>
<td>10</td>
<td>What was industrialized on the island?*</td>
</tr>
</tbody>
</table>

* Two responses expected.
Table 10  
Shows the result of the testing response variables for Experiment 2.

<table>
<thead>
<tr>
<th>Response Variables</th>
<th>Original</th>
<th></th>
<th>Simplified</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE*)</td>
<td>%Correct</td>
<td>Mean (SE*)</td>
<td>%Correct</td>
</tr>
<tr>
<td>Number of States Identification</td>
<td>0.50 (0.25)</td>
<td>50%</td>
<td>0.63 (0.25)</td>
<td>63%</td>
</tr>
<tr>
<td>Number of Correct Response (11 Rs)</td>
<td>5.25 (0.92)</td>
<td>48%</td>
<td>8 (0.38)</td>
<td>73%</td>
</tr>
<tr>
<td>Response time (all 10 Qs)</td>
<td>28 (4.86) min</td>
<td></td>
<td>31 (4.56) min</td>
<td></td>
</tr>
<tr>
<td>Difficulty</td>
<td>4 (0.46)</td>
<td></td>
<td>3 (0.27)</td>
<td></td>
</tr>
<tr>
<td>Lack of Confidence</td>
<td>3.63 (0.46)</td>
<td></td>
<td>2.5 (0.33)</td>
<td></td>
</tr>
<tr>
<td>SUS survey (out of 100)</td>
<td>51.56 (5.66)</td>
<td></td>
<td>61.60 (8.59)</td>
<td></td>
</tr>
</tbody>
</table>

*SE = Standard Error Mean

6.2.5. EXPERIMENTAL DESIGN AND ANALYSIS

Each participant was presented with one diagram (randomly chosen from a set of two) for simplification and the other diagram (of the two) for no simplification. For each diagram there were a total of 10 questions to answer. The question about the number of states in a country was considered its own variable and separately evaluated from the other questions. There were 9 other questions, all of which related features on the map; the latter
two questions expected two answers each. The total number of correct responses (out of 7 +2*2 = 11) was recorded. The total time to respond to all 10 questions was also recorded. At the end of their responses for each diagram, participants were also asked the difficulty of the task on a scale of 1 to 5 and their lack of confidence on a scale of 1 to 5.

A similar statistical analysis was used as in Experiment 1 for the number of correct responses, time taken, difficulty and lack of confidence. For the question about number of states per diagram, a related-samples McNemar Test is considered instead of the RSWSRT as it applies to binary data. In addition, the procedure for calculating the SUS survey given in (Brooke, 1986) was followed.

6.2.6. RESULTS AND DISCUSSION

For both types of diagrams, once exploration started, a similar strategy was used: all participants moved the device in a random manner until they felt tactile feedback. They then stopped at that position to feel and identify the feature before either continuing exploration or answering a question. In more detail, some participants found the borders first and then explored inside them for features; whereas, some found the features first and then explored further to find the borders. The fact that the strategy did not change between using a simplified and a non-simplified diagram is not surprising as the type of material was still the same, only the amount changed.

Where the difference lay was that for those diagrams that the run time simplification selection was offered, it was always used by a participant. All the
participants, except P2 and P4, did spend time exploring the original diagram before
deciding to change the feature types on the diagram. P2 and P4 had an interesting strategy
in that as soon as they were presented with the testing diagram, they selected the option to
only present the boundary map so that they could explore it first before adding features to
it. Most of the participants liked the use of simplification. In contrast, one participant (S7)
got very frustrated with the diagram without simplification and decided to stop the trial
before completing the questions (after 11 minutes). However, one participant (P6) had
some trouble with locating any features on the simplified map for industries and preferred
using the original map for which features were detected more frequently.

In terms of actually presenting features, all participants seemed to like the grouping
of individual feature within the feature types except participant (P4) who mentioned that
she would prefer only one feature to be displayed at a time. One issue we did not anticipate
is the confusion caused by features that overlapped, such as a coal field on a mountain or a
city surrounded by forest. This may be due to blurring of the tactile signals when the
device is moved quickly or due to difficulty in discriminating the features. For example,
participant P3 and P5 both mentioned that they confused the river and coal features; this
was likely due to both moving in a downwards direction (one in a north-south direction,
one at an angle). However, in general, all participants liked the use of the tactile
animations and found the features, within each feature type, to be easily distinguishable.
In the future, the legends on the display will not be included as at least two participants (P1
and P3) found them distracting and the legends are not needed if auditory feedback about a
feature is given on demand.
In examining the response variables, the odds of correctly answering a relational question about features (questions 2-11) greatly increased with simplification by a factor of 227% (i.e., an odds ratio of 3.27). Using a RSWSRT (as the data was not normally distributed), it was found that this difference was significant (p = 0.046). The odds ratio of correctly indentifying the number of states also increased with simplification by a factor of 67% (i.e., an odds ratio of 1.67). However, using a related-samples McNemar Test (as the data was not normal), it was found that this difference was not significant (p = 1.00). The latter was unexpected, as all participants selected to show only the boundaries in the simplified condition. This may due to the borders being a significantly different type of stimulation than the other features (i.e. vibration cf. animation). This seems to suggest that caution is needed when interpreting the results for contextual simplification as, perhaps, another tactile feature set may produce different results. However, it should be noted that through pilot testing, we did try to maximize the discrimination between features.

The time taken to perform the tasks was actually marginally slower for the condition using simplification than for the non-simplified condition (with a difference of 2.63 minutes). However, using the RSWSRT (as the data was not normal), did find this difference to be significant (p = 0.553). The extra time needed for the condition using simplification was likely in part due to the time needed to select the features to be displayed. It may also reflect more time taken to obtain more accurate answers: it is possible in the original diagram that participants got frustrated and “gave up” (as was clearly indicated by S7).
The difference in the difficulty ratings of performing a task was noticeably better (a difference of 1.0 on a scale of 1 to 5) for the simplified condition versus the original map. However, using a RSWSRT (as the data was not normal) it was found not significant (p=0.107). Similarly for the lack of confidence ratings, using simplification was noticeably better (a difference of 1.1) but not statistically so (p = 0.123). In addition, although the SUS survey produced a difference of 10.04 (on a scale of 0 to 100), it also was not significant (p = 0.244). However, qualitative comments of the users showed that they really loved the ability of adding or removing the features on the diagram. Based on the improvements in performance in answering questions correctly and the enthusiasm of the participants, we believe that contextual simplification is still worth exploring. However, the results on the difficulty, lack of confidence and SUS ratings suggests that there is room for improvement in developing a more effective system.

6.3. CONCLUSION

As it is more difficult for the tactile system to interpret outline forms as compared to vision, the amount of information presented in visual diagrams is typically too much to be realistically interpreted through its tactile counterpart. Simplifying the diagram plays an important role in making a tactile diagram accessible to individuals who are blind or visually impaired. However, currently this is performed by the maker of the diagram, not the user, and typically focuses on one particular task. The advent of refreshable tactile displays attached to a computer raises the possibility of developing software tools that can
be used by an individual who is blind or visually impaired to, themselves, actively control how a tactile diagram is simplified and allowing this to change with any given instance of use.

The purpose of this study was to investigate whether two types of simplification, which could be automated, namely, boundary and contextual simplification, warrant further investigation. For boundary simplification, a very large improvement (odds ratio of 6.38) was found in correctly describing the overall shape of a boundary. This suggests that the idea of boundary simplification should be explored further. It is also supported by statistically significant but weak improvements in the ease of doing a task and confidence in doing a task. Although not statistically significant, the response time was also reduced. Together these results suggest that boundary simplification is useful, but the algorithm used may not be optimal. We believe this warrants further investigation.

For contextual simplifications, where users were allowed to perform “filter” and “relate” tasks to answer questions, we found that performance, as described by the number of answers correct, greatly improved (odds ratio of 3.27). Although the ease in answering the questions and the confidence in the answers both improved with using contextual simplification, as did the SUS survey, the differences were not found to be significant. However, the strong qualitative comments that the users gave in support of contextual simplification, as well as the improvement in the answers, suggest to us that further exploration of contextual simplification is warranted. It should be noted that the time taken for contextual simplification increased (rather than decreased as was expected) as compared to using the original diagram; however, this may reflect the additional time
needed to do selections of the simplification and/or participants “giving up” in the non-simplified condition.

Two of the major limitations in drawing strong conclusions from our study is the relatively low number of participants and that only one diagram type (and in the case of Experiment 2, only one diagram per condition) were used. Although these limitations exist, they were necessary in order to obtain relatively quick feedback on the direction of our project. Unfortunately tactile graphics, particularly when accessed with haptic devices, are very time consuming to use. Therefore, at this preliminary stage, we felt that these limitations were acceptable. In the future, a larger number of participants and a larger variety of diagram types and questions will be used.

In addition, there are also potential limitations in the methods used that may have affected performance: that is to say, we may have not chosen the most effective methods for boundary or contextual simplification. It is possible that boundary simplification may be better performed with curves rather than lines, or that the contextual simplification, as one user suggested, be selected for single features rather than a feature type. In addition, the use of vibration and the animation may, despite pilot testing, not be optimal. Finally, another aspect of the design that may have an impact is to have the diagrams presented from simple to more complex on the demand of the user, rather than from complex to simple. However, based on the experimental results and comments of the participants, we believe that both methods of simplification have potential and warrant further exploration.
7. TESTING DYNAMIC TACTILE PRESENTATION METHODS FOR ACCESSING OVERLAPPING INFORMATION IN GRAPHIC DIAGRAMS

In this chapter, we present the second study that was performed towards the development of the automated simplification tool for AHUI. The results of the previous preliminary study confirmed our hypothesis and showed the need of the development of the automated simplification tool. However, we found that participants, when using the contextual simplification participants had difficulty accessing overlaying information. Hence, instead of the development of the automated simplification tool which we believe could be done by following the methods that we discussed in Chapter 2. In this study, we concentrated on a more fundamental issue of how to effectively present visual information using haptic displays. We considered it a higher priority as we believed that if left unsolved this issue could negatively affect the performance of participants during the testing of automated simplification tool.

7.1. METHOD

The main intent of this study was to compare the usability of three presentation methods for retrieving relational information between two sets of spatially overlapping
information in a dynamic environment (i.e., on a computer) by individuals who are blind and visually impaired. The first method uses two different diagrams, one for each set of data, that the user can toggle between (i.e., Tactile-Tactile Switch or TTS). The second method uses a single tactile diagram, where the two different sets of information are presented by two different dimensions (i.e., Tactile-Tactile Overlap or TTO). The third method uses a single diagram, but two different modalities to represent the two sets of information (i.e., Tactile Sonification Overlap or TSO). Tactile information was presented with a refreshable haptic display device, whereas, the auditory feedback was presented using the sound card that came with the computer. To assess performance improvements with the different presentation methods five testing measures; two objective and three subjective measures were used. The objective measures used were; (a) the number of correct answers to six questions about a map, and (b) the total time to answer those questions. The subjective measures used were: confidence in the answers, perceived difficulty and usability. Participants were asked to rate their confidence in using the given method for the particular diagram, as well as the perceived difficulty. At the end of the experiment, participants were asked to answer questions on the System Usability Scale Survey (Brooke, 1986) for each of the presentation methods.

7.1.1. EXPERIMENTAL DEVICE AND SETUP

A refreshable haptic display device (Owen et al., 2009) as shown in Figure 12b was used in this study. The device consisted of: (a) a multi-pin tactile display and its associated
hardware and software, and (b) hardware and software for tracking the position of the
tactile display. The general idea of the device was that the graphical information was
represented as a virtual diagram inside the computer. The position of the tactile display in
the work area was sensed and this was mapped on to a location in the virtual diagram.
From this, the position of each of the pins in the virtual diagram was determined, and
whether the pin was to be raised, lowered or vibrating at a particular frequency,

For the actual tactile display, a refreshable Braille cell (Metc AG., 2010)
consisting of a matrix of eight tactile pins (4x2) was used. It was mounted inside a hollow
mouse case (chosen as a low-cost method to achieve a good ergonomic design) with the
pin matrix replacing the scroll wheel (Figure 12a). Each pin was 1 mm in diameter and
spaced 2.5 mm apart. The eight pins were controlled in parallel using relays (external to
the mouse case) that determined the applied voltage to the piezoelectric actuators. A
software driver was written for the device in Labview for which a user could specify
whether each tactile pin is raised or lowered, and what frequency it should vibrate at.

A graphics tablet (Adesso 12000; Adesso Inc., 2011) was used to keep track of the
position of the tactile display as, unlike an optical mouse, it is an absolute rather than a
relative pointing device: this was a critical design decision as distortions due to relative
pointing devices (see Rastogi and Pawluk, 2010a) make it difficult to infer diagram
properties such as lengths, angles and shapes. Rather than use the transmitter coil that
came with the graphics tablet, we made our own transmitter circuit tuned to the given
tablet. The transmitter coil was mounted directly under the tactile display to improve
spatial collocation between the kinesthetic and tactile information (Rastogi and Pawluk,
2010a). To access the pointer’s location, pre-existing software commands built into the language used (MathWorks Inc., 2012) were utilized. A frame around the tablet is used to prevent the users from moving out of the tablet screen (Figure 12b).

The device also contained 4 programmable buttons (Figure 12a). For this experiment, the bottom left button (Button 3) was programmed to produce auditory feedback about the name of the feature or features at that point on the display when clicked. The bottom right button (Button 4) was programmed to close the program when clicked. The two top buttons (Button 1 on the left and Button 2 on the right) were only used for the TTS method. For this method, Button 1 selected the first of the paired diagrams to present one set of features, and Button 2 presented the second diagram with the other set of features.

7.1.2. EXPERIMENTAL STIMULI

A total of 3 training diagrams and 18 testing diagrams were created for this study. All diagrams consisted of make-believe features, to avoid biasing the results from any previous knowledge of any particular diagram. Two different types of testing diagrams, were used: (a) geographical maps that overlaid areas in which agricultural crops were grown on top of states of a given country, and (b) a multi-level floor plan for a train station, where the bottom floor contained different train tracks on which a given train is to be found and the top floor contained a variety of stores beside staircases down to the train tracks. Testing diagrams consisted of sets of 9 geographic maps and 9 multi-floor train
stations. For the geographical maps, all maps consisted of 5 different states, indicated by state 1 through state 5 (Figure 33, upper-left corner), and five different crops of fruit that are grown, namely. “apple”, “banana”, “mango”, “grapes” and “oranges” (Figure 33, upper-right corner). For the train station, all maps consisted of 5 different train tracks, indicated by track 1 through track 5 (Figure 33, lower-left corner), and 5 different stores, namely “food”, “coffee”, “convenience”, “clothes” and “book” (Figure 33, lower-right corner). For all the testing diagrams, the position and shapes of the features were randomized to prevent any biasing. For each map, a set of 6 relational questions were asked of the participants (Table 11).
Figure 33: Testing diagrams used in the study. (1) Geographic maps of random country, (top left) showing the 5 different states with shades of gray and (top right) showing the 5 different fruits grown in the same country. (2) Multi-floor maps of a random train station, (bottom left) showing the 5 different stores on one of the floors and (bottom right) showing 5 different train tracks present on the basement floor. *diagrams shown in this figure have been converted to gray scale from colors for illustration purpose only.
Table 11

Relational questions asked for the two types of testing diagrams.

<table>
<thead>
<tr>
<th>Diagram Type</th>
<th>Number</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic</td>
<td>1</td>
<td>Which fruit grows in state 3?</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Which is a common fruit grown in 2 states and only 2 states?</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Which is a common fruit grown in 3 states and only 3 states?</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Which state grows mangoes?</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Which states grows 1 and only 1 type of fruit?</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Which states grows 2 and only 2 types of fruits?</td>
</tr>
<tr>
<td>Floor plan</td>
<td>1</td>
<td>Which track runs under the &quot;fast food&quot; store?</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Which is a common track running under 2 stores and only 2 stores?</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Which is a common track running under 3 stores and only 3 stores?</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Which store has track 5 running underneath it?</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Which store does not have any track running under them?</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Which stores have 2 and only 2 tracks running under them?</td>
</tr>
</tbody>
</table>

Two different types of training diagrams were used in the study. One of the three training diagram consisted of 15 colored blocks, 3 column and 5 rows, each block representing one of the fifteen testing stimuli. This diagram was used to allow participants
get familiarized with all the testing stimuli and be able to compare them side by side. The other two training diagrams were simplified versions of the two types of testing diagrams, containing fewer features, and used to train participants on the testing methods.

### 7.1.3. PRESENTATION METHOD

In the *tactile/tactile toggling* method (TTS), participants were required to toggle between two diagrams to determine the answer to the relational questions asked. When toggled, the cursor remained in the correctly corresponding position on the new diagram but the features changed to the second feature set. In terms of features, there are several different parameters that could be used for the two different maps: temporal parameters, such as temporal frequency, temporal duty cycle, frequency modulation and rhythm, and spatial parameters, such as spatial pattern, spatial frequency, spatial duty cycle, and spatial modulation; other parameters such as amplitude and waveform shape cannot be used as the pins can only be raised or lowered (i.e., are binary). Work within our laboratory (Burch et.al., 2011) and others (Kyung et.al., 2005; Murray et.al., 2003; Ternes & MacLean K, 2008), found temporal frequency to be a very effective parameter, particularly if selected on a logarithmic scale: we, therefore, selected temporal frequencies of 10, 20, 40, 80 and 130Hz (the latter was chosen off the scale due to the limitation in the temporal bandwidth of the haptic device) to represent at least one of the feature sets.

The question is what parameter should be chosen for the other set of features. This is of relevance as the parameter chosen may affect the results of the intended comparison.
between the TTS, TTO and TSO methods. At one extreme, we could use vibration (the same parameter as for the first set of features). At the other extreme, spatial parameters are the most different from temporal vibration. In initial exploration of these parameters, using spatial patterns produced the most different parameter than temporal frequency. However, the spatial patterns were not very salient. Therefore, the spatial patterns were turned into “animations” (Pietrazak et al., 2009; Figure 34) which were temporally sequenced at a frequency (0.66 Hz) well below the temporal vibrations. We then performed a pilot study to examine whether selecting one dimension (i.e., the “extreme” case of the same parameter) versus another (i.e., the opposite “extreme” case of low frequency modulated spatial patterns) would make a difference in performance.

![Patterns](image-url)

Figure 34: Continuous tactile patterns used in the study.

For the tactile/tactile overlapping method on the same diagram (TTO), participants were required to interpret two sets of features on the same diagram to answer relational questions asked with both features being represented by tactile parameters. Obviously using the same parameter for both feature sets would be very difficult to interpret. We,
therefore, selected the most different parameters, while ensuring that both are salient. For one feature set we varied temporal frequency, as described above. For the other feature set, we chose the “animations” also described above. Thus, we expected that the TTO method used the most effective parameter out of the ones we explored.

For the *tactile/sonification overlapping method* on the same diagram (TSO), participants were required to interpret two sets of features on the same diagram to answer relational questions asked, with one feature set represented by a tactile parameter and one by a sonification parameter. As described above, there are several different parameters that could be selected to describe the tactile set of features. For sonification, there are also several different temporal parameters that could be used, such as temporal frequency (pitch), temporal duty cycle, frequency modulation, rhythm, timber, and attack and decay (Brewster et. al., 1999; Gaver, 1993; Hermann et.al., 2011; Kramer, 1994; Mynatt, 1992). Brewster and colleagues (1993), in an effort to compare the different parameters found that musical timbre performed better as compared to simple tones of varying pitch but by a very small amount. Several other researchers have implemented pure tones with varying pitch in their application (Dieberger A., 2011; Lee et.al., 2001). Using small duration tones are easier to use and require less training (Hermann et.al., 2011). Hence for our sonified feature set, we chose to use temporal frequency as it is simple and easy to differentiate several frequencies, particularly if also selected on a logarithmic scale. We used frequencies of 150, 300, 600, 1200 and 2400 Hz.

However, for TSO, as with TTS, it was not clear what should be chosen for the tactile parameter or if the choice will have an effect on the comparison with the TTS and TTO
methods. Therefore, we performed a pilot experiment to determine if the most different, but salient, tactile parameters would have an effect on performance. In one condition we used tactile temporal frequencies (as described above) and in the other condition we used low frequency sequenced “animations” (also described above).

7.1.3.1. PILOT STUDY

A pilot study was performed to examine how sensitive choosing the parameters for the TTS and TSO methods were on performance of these methods. For the TTS method, the parameter for one feature set was chosen to be tactile temporal frequency and the parameter for the other feature set was either of two salient tactile “extremes” (temporal frequency or low frequency sequenced “animations”). For the TSO method, the parameter for one feature set was chosen to be auditory temporal frequency and the parameter for the other feature set was either of the two salient tactile “extremes” given above. For the TTO set, it was assumed that choosing the two most salient tactile “extremes” would be most effective, and, in preliminary work, these were found to be temporal frequency and low frequency sequenced “animations”.

7.1.3.1.1. PARTICIPANTS

A total of seven (6 male and 1 female, mean age of 24 ± 2) sighted individuals participated in this study. All participants were students and were naïve to the haptic
device and had no experience using the device. None of the participants had any experience using the tactile diagrams or any neurological disorders.

7.1.3.1.2. TESTING DIAGRAMS

A total of five make believe geographic diagrams were created for this study. All maps consisted of 5 different states, indicated by state 1 through state 5 (Figure 34, upper-left corner), and five different crops of fruit that are grown, namely “apple”, “banana”, “mango”, “grapes” and “oranges” (Figure 34, upper-right corner). One diagram out of the 5 was used as a training diagram.

7.1.3.1.3. TESTING PROCEDURE

The haptic device described in Section 2.1 was used to present the tactile feedback and speakers attached to the computer were used to present the audio feedback. Participants were blindfolded during the entire duration of the study, the haptic device was placed in front of the participants at a comfortable height and the volume set on the speakers so that participants could easily hear the audio feedback. The study was divided into two sessions. During the first session, participants were given training on the fifteen (5 tactile animations, 5 tactile vibrations and 5 sonification feedbacks) different sensations that would represent the features. This training took around 2-5 minutes. During the
second session, participants were trained and tested on four different methods of presenting
the features.

Two of the methods fell under the umbrella of the TTS method and were, for the
two feature sets: (1) tactile temporal frequency – tactile temporal frequency, and (2) tactile
temporal frequency – tactile animations. The other two methods fell under the umbrella of
the TSO method and were, for the two feature sets: (1) sonified temporal frequency –
tactile temporal frequency, and (2) sonified temporal frequency – tactile animations. The
two different methods using the TTS presentation method were presented first,
counterbalanced between the two different methods. For each method two diagrams were
used, drawn from a pool of four, counterbalanced across participants and uncorrelated with
the method used. The two different methods using the TSO presentation method were
presented second, counter balanced between the two different methods. Two diagrams
were used for each method in the same manner as for the TTS methods.

During the training session for each method, participants were taught how: (1) the
device and buttons work when exploring the tactile diagram, (2) to explore the tactile
diagrams to find the features present on the diagram, and (3) to familiarize with the
specific feedback provided for the given method. Training continued until participants
were able to correctly identify the features present on the map. This lasted approximately
15 minutes. During the testing session, for each diagram, participants were asked to
respond to 7 questions. The response time to complete all 7 questions and the number of
button clicks used to retrieve word labels were also recorded. Following this, participants
were asked to rate the confidence and difficult of the task on a scale of 1 (very
confident/very easy) to 10 (not very confident/very difficult). After completing the testing session, participants were asked to rate the usability of the method on a scale of 1 (non usable) to 100 (most usable). Each participant received a 1-2 min break after every diagram to relax and rest their fingers. For analyzing the results, all the responses of the participants were averaged, except for one, the number of correct response, where the total number of correct responses (out of 14) was used.

### 7.1.3.1.4. RESULTS

We observed that all participants used random exploration to find the features on the diagram, occasionally using horizontal or vertical sweeps. The mean performance for the four different methods and their standard error are presented for the number of correct responses, the response time, difficulty, confidence and usability in Table 12. In comparing the results, non-parametric statistics were used due to the relatively small sample size. Statistics were performed in SPSS. When comparing the two different TTS methods, we did not find any statistical difference between the number of correct responses (p = 0.399) or the response times (p = 0.399). We also did not find any differences in the difficulty (p=0.344), confidence (p=0.352) or usability (p=0.734). However, when asked about the preference of the testing cases, 4 out of 7 participants preferred the temporal frequency-temporal frequency case, as compared to tactile animation-temporal frequency. When comparing the two different TSO methods, we also did not find any statistical difference between the number of correct responses (p=0.115) or the response times (p=0.609).
There were also no differences in the difficulty (p=0.112), confidence (p=0.336) or usability (p=0.15). However, again, when we asked participants about their preference at the end of experiment, 4 out of 7 participants preferred sonification frequency - temporal frequency over sonification frequency - tactile animation.

Table 12
Results of pilot study

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Toggle</th>
<th>Overlap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TTF-TA</td>
<td>TTF-TTF</td>
</tr>
<tr>
<td></td>
<td>Mean (SE)</td>
<td>Mean (SE)</td>
</tr>
<tr>
<td>Correct Response</td>
<td>6.71 (0.87)</td>
<td>7.43 (1.15)</td>
</tr>
<tr>
<td>Response Time</td>
<td>17.86 (3.16)</td>
<td>16 (2.60)</td>
</tr>
<tr>
<td>Difficulty Rating</td>
<td>5.39 (0.86)</td>
<td>4.18 (0.67)</td>
</tr>
<tr>
<td>Confidence Rating</td>
<td>5.68 (0.62)</td>
<td>5.29 (0.72)</td>
</tr>
<tr>
<td>Usability Rating</td>
<td>54.29 (7.11)</td>
<td>52.86 (8.30)</td>
</tr>
</tbody>
</table>

* TTF= Tactile Temporal Frequency, TA= Tactile Animation, TSF= Tactile Sonification Frequency; **SE= Standard Error
7.1.3.2. CONCLUSION

In this pilot study, we tested how sensitive the TTS and TSO presentation methods would be to the choice of parameters describing the two different feature sets. For the TTS method, we compared using tactile temporal frequency-tactile temporal frequency to tactile temporal frequency-tactile animation. In terms of the objective measures used (number of correct responses and time taken), there was no statistical significant difference. The same was true for difficulty, confidence and usability. This suggests that the TTS presentation method was not very sensitive to the parameters used. As temporal frequency is one of the easier parameters to learn and interpret, we chose the tactile temporal frequency-tactile temporal frequency to use for the main experiment. For the TSO method, we compared using sonified temporal frequency-tactile temporal frequency to sonified temporal frequency-tactile animation. Again, there were no statistical significant differences between the two alternative for both the object and subjective measures. This suggests that the TSO presentation method is not very sensitive to the parameters used. Again, as temporal frequency is one of the easier parameters to learn and interpret, we chose the sonification temporal frequency-tactile temporal frequency.

There were two main limitations, inherent in the nature of pilot studies, in that there were a small number of participants and only a single type of diagram was used. However, all the trends in the data suggest that using tactile temporal frequency versus tactile “animations” (i.e., the two salient “extremes’) could possibly result in better performance. This suggests that using tactile temporal frequency is the most appropriate choice for
comparing the different methods, as we also chose the best performing parameters for the TTO method.

### 7.1.4. PARTICIPANTS

A total of twelve individuals who were either blind or visually impaired participated in this study. Details about the participants that are relevant to the experiment are shown in Table 13. None of the participant had any neurological disorder or diabetes. Those participants who had experience with haptic devices had it from participation in previous experiments in the lab, some of which used the same device used in this study. All participants received financially compensated for their voluntary participation in the study. The study was approved by the International Review Board (IRB) and followed the tenets of the declaration of the Helsinki on research involving human subjects.
<table>
<thead>
<tr>
<th>No</th>
<th>Age</th>
<th>Sex</th>
<th>Vision</th>
<th>Vision Loss</th>
<th>Haptic Device Experience</th>
<th>Tactile Diagram Experience</th>
<th>Dominant Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>M</td>
<td>20/2450 (R); 20/800 (L)</td>
<td>Congenital</td>
<td>No</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>F</td>
<td>20/2300 (R); 20/2250 (L)</td>
<td>Congenital</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>M</td>
<td>20/2400 (R); no vision (L)</td>
<td>Congenital</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>M</td>
<td>20/600 (R); 20/800 (L)</td>
<td>Congenital</td>
<td>Yes</td>
<td>Yes</td>
<td>Left</td>
</tr>
<tr>
<td>5</td>
<td>43</td>
<td>F</td>
<td>Totally Blind</td>
<td>Age 2</td>
<td>Yes</td>
<td>No</td>
<td>Right</td>
</tr>
<tr>
<td>6</td>
<td>62</td>
<td>F</td>
<td>Totally Blind</td>
<td>Age 50</td>
<td>Yes</td>
<td>Yes</td>
<td>Right</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
<td>M</td>
<td>Totally Blind</td>
<td>Congenital</td>
<td>No</td>
<td>No</td>
<td>Right</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
<td>M</td>
<td>no vision</td>
<td>Congenital</td>
<td>Yes</td>
<td>No</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(R); 20/800 (L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>----------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>M</td>
<td>Totally Blind</td>
<td>Congenital</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>F</td>
<td>20/2300 (R); 20/2300 (L)</td>
<td>Age 43</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>59</td>
<td>F</td>
<td>Totally Blind</td>
<td>Age 4</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>46</td>
<td>M</td>
<td>20/600 (R); 20/25(L)</td>
<td>Age 40</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

* (R) = right eye, (L) = left eye,

### 7.1.5. EXPERIMENTAL PROCEDURE

The study was performed over two days to avoid fatigue due to the long duration of the study. On day one, participants were trained on how to use the device, followed by training and testing on one of the testing methods. On day two, they were trained and tested on the other two testing methods. The presentation of the testing methods was counterbalanced across participants. Participants were blindfolded during the entire duration of the study and the haptic device was placed in front of the participants at a comfortable height. Auditory feedback was played through a speaker connected to the
computer. Participants were also allowed breaks during both the training and testing to avoid fatigue.

On the first day, participants were first given training on the fifteen types of feedback (5 tactile waveform patterns, 5 tactile vibrations and 5 auditory vibrations) using the given training diagram, to familiarize with the different stimuli sensations. The five waveform patterns are shown in Figure 35. The 5 tactile vibrations were 10, 20, 40, 80, and 130 Hz, and the 5 auditory vibrations were 150, 300, 600, 1200 and 2400Hz. This training took approximately 3-5 minutes. Participants were then informed that during the testing they would only feel 5-10 of these tactile stimuli on a single diagram. They were also trained on using Button 3 to obtain the information (e.g., type of fruit and/or state) at the given spatial location they felt the stimulation.

Training on how to use each method of presentation occurred immediately before testing of that method. One method was trained and tested on Day 1 and two methods were trained and tested on Day 2. During each training session, participants were taught: (1) how to explore the tactile or audio-tactile diagrams to find the features present, (2) use the buttons of the display device for that particular method, and (3) familiarize themselves with the tactile and auditory stimuli. Training continued until participants were able to correctly identify the features present on the two training maps (one of which was a geographical map and one of which was a map of a multi-level train station). Each of these training session lasted on an average of 6 (SD=8) minutes, with the least time taken for TTS 3.5 (SD=4.16) minutes and approximately same time for TTO 7.32 (SD=9.10) and TSO 7 (SD=8.27).
During the testing session for each presentation method, participants were presented with 6 diagrams (3 geographic & 3 multi-floor maps). Each of the three maps of a given diagram type were drawn from a pool of 9 maps and counterbalanced for (but uncorrelated with) the 3 presentation methods across participants. The two sets were also uncorrelated with each other. In addition, the order of presenting the two types of maps was counterbalanced across participants. When performing the experiment, each participant was given a one to two minute break after every diagram to relax and rest their fingers. For each diagram, participants were asked to respond to 6 questions (Table 11). The overall time to answer all questions was recorded, as well as the number of button clicks to access the auditory text descriptions were recorded. Participants were also asked to rate the confidence and difficult of the presentation method on a scale of 1 (very confident/very easy) to 10 (not very confident/very difficult). After completing three diagrams of same type, participants were asked to take a System Usability Scale Survey (Brooke, 1986) and make comments about the testing method. The questions contained in the System Usability Scale Survey are given in Table 14. On the second day, after completing all the testing methods, participants were asked to rate their preferences of methods, where they were asked to list the three methods from to 1 to 3, as the ones they would prefer to use personally for testing tasks.
Table 14
System usability scale survey questionnaire.

<table>
<thead>
<tr>
<th>No</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I think that I would like to use this system frequently</td>
</tr>
<tr>
<td>2</td>
<td>I found the system unnecessarily complex</td>
</tr>
<tr>
<td>3</td>
<td>I thought the system was easy to use</td>
</tr>
<tr>
<td>4</td>
<td>I think I would need the support of a technical person to be able to use this system</td>
</tr>
<tr>
<td>5</td>
<td>I found the various functions in this system very well integrated</td>
</tr>
<tr>
<td>6</td>
<td>I thought there was too much inconsistency in this system</td>
</tr>
<tr>
<td>7</td>
<td>I would imagine that most people would learn to use the system very quickly</td>
</tr>
<tr>
<td>8</td>
<td>I found the system very cumbersome to use</td>
</tr>
<tr>
<td>9</td>
<td>I felt very confident using the system</td>
</tr>
<tr>
<td>10</td>
<td>I needed to learn a lot of things before I could get going with the system</td>
</tr>
</tbody>
</table>

7.1.6. STATISTICAL METHODS

Statistics were performed using SPSS (IBM, Inc.). The primary variable for comparing the three testing methods was the number of correctly answered relational questions. Six secondary variables were also used. First, on a per diagram basis (similar to the number of correct) were: response time, number of button clicks, confidence and
difficulty. Second, on a per presentation method basis was the System Usability Scale Survey (Brooke, 1986). Finally, the rankings of the methods were also compared. For the first five variables General Estimating Equations (GEEs) were used to model the data. GEEs were chosen because these models can handle a variety of distributions for the response variable (e.g. normal, binomial, Poisson) and can account for both between and within subject sources of variation. This was particularly relevant for the first three variables which were more appropriately modeled by Poisson distributions. Although non-parametric tests could be used, they would not be able to take advantage of the increase in power of the experimental design, which had repeated measures across within sources of variation. However, a non-parametric test was used for the rankings as there was only one measure per presentation method and the data was treated as ordinal.

The models for number of questions correct, number of button clicks, time taken, confidence and difficulty included effects for presentation method (TTS, TTO, TSO), diagram set (geographical map or multi-level floor map) and diagram order (1, 2, 3) nested within diagram set. For the first three variables (number of questions correct, number of button clicks and time taken) a Poisson distribution was used with a loglinear link. For the last two variables (confidence and difficulty) a normal distribution with an identity link was used. For all variables, the statistical significance of the main model variables and their interactions were examined. As it was primarily the presentation method that we were interested in, the effect size was only calculated for this main effect. To further analyze the data: if presentation method was statistically significant, pairwise contrasts between the different methods were performed.
To examine the participants’ satisfaction with the different presentation methods, the overall scores for the system usability scale survey (SUS) for the six different conditions of presentation method x diagram type were determined according to the method described by Brooke (1986). This involved: (1) subtracting one from the scores of statements 1, 3, 5, 7 and 9, which are expected to increase with increased usability, (2) subtracting from five the scores of statements 2, 4, 6, 8, 10, which are expected to decrease with increased usability, and (3) then multiplying the total of the usability scores for all 10 statements by 2.5 to create an overall score that can be interpreted as 0 (non-usable) to 100 (highly usable). The overall scores were then compared between groups using GEEs. The model included effects for presentation method (TTS, TTO, TSO) and diagram set (geographical map or multi-level floor map). In addition, a normal distribution was used to describe the data with an identity link.

7.2. RESULTS

7.2.1. NUMBER OF CORRECT RESPONSES

The model of the number of correct responses per diagram was modeled using GEEs assuming a Poisson distribution for the response variable and a loglinear link function. The estimated mean number of correct responses (out of 6) for the three presentation methods is summarized in Table 15. Results of the analysis of model effects showed that there was evidence of a significant presentation method effect (Wald Chi-Square(2,
N=216)= 36.0, p-value < 0.001), thus there were significant differences in the number of correct responses for the three different presentation methods. There was also a significant effect of the interactions between Method x Diagrams (Wald Chi-Square(4, N=216) = 25.5, p-value < 0.001), suggesting that there were different learning effects for the different presentation methods during the testing, and Method x Diagram Type x Diagrams (Wald Chi Square(4, N=216)=17.8, p-value = 0.001). The TSO method increased the percent correct by 21% as compared to the TTS method, whereas the TTO method only increased the percent correct by 4%. Examining pairwise contrasts for the different presentation method: the TSO method was significantly different than both the TTS method (p < 0.001) and TTO method (p < 0.001), whereas there was no significant different between the TTS and TTO methods. Thus, the TSO method improved the likelihood of having more correct responses.
Table 15

Estimates of objective testing variables used in the study

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Method</th>
<th>Mean</th>
<th>SE</th>
<th>95% Wald CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper</td>
</tr>
<tr>
<td>Correct Response</td>
<td>TTS</td>
<td>2.31</td>
<td>0.21</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
<td>2.55</td>
<td>0.19</td>
<td>2.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>3.57</td>
<td>0.18</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.93</td>
</tr>
<tr>
<td>Response Time</td>
<td>TTS</td>
<td>556.21</td>
<td>43.69</td>
<td>476.84</td>
</tr>
<tr>
<td>(in sec)</td>
<td></td>
<td></td>
<td></td>
<td>648.79</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
<td>826.67</td>
<td>71.73</td>
<td>697.38</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>979.93</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>546.43</td>
<td>39.67</td>
<td>473.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>629.98</td>
</tr>
<tr>
<td>Button Click</td>
<td>TTS</td>
<td>74.17</td>
<td>4.42</td>
<td>65.99</td>
</tr>
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<td></td>
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<td>83.37</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
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<td>9.03</td>
<td>82.90</td>
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<td></td>
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<td>118.49</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>75.07</td>
<td>9.09</td>
<td>59.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95.18</td>
</tr>
</tbody>
</table>

* CI= Confidence Interval, SE= Standard Error

7.2.2. RESPONSE TIME

The model of the time taken per diagram was modeled using GEEs assuming a Poisson distribution for the response variable and a loglinear link function. The estimated mean time taken (in seconds), for the three presentation methods, is summarized in Table 15. Results of the analysis of model effects showed that there was evidence of a significant presentation method effect (Wald Chi-Square(2, N=216) = 21.9, p-value <
0.001), thus there were significant differences in the time taken per diagram for the three different presentation methods. The estimated mean for the TTO method was 286 seconds and 280 seconds greater than for the TTS method and TSO method, respectively. The difference between the TTS method and TSO method was only 9.8 seconds. Examining pairwise contrasts for the different presentation method: the TTO method was significantly different than both the TTS method (p < 0.001) and TSO method (p < 0.001), whereas there was no significant different between the TTS and TSO methods. Thus, the TTO method significantly increased the time to perform the relational task. There was also a significant main effect of Diagram Presentation Order (Wald Chi-Square(2, N=216) = 28.9, p-value < 0.001) and Method x Diagram Type x Diagrams (Wald Chi Square(4, N=216)=18.2, p-value = 0.001). The effect of diagram presentation order was indicative of the fact that learning occurred across trials and so the diagrams were completed increasingly faster in the sequence (i.e., means in order were 734 with SE=47.0, 621 with SE= 33.0 and 550 with SE=30.4 seconds).

### 7.2.3. NUMBER OF BUTTON CLICKS FOR THE FEATURE TEXT

The model of the number of button clicks to access the auditory text describing the feature(s) was modeled using GEEs assuming a Poisson distribution for the response variable and a loglinear link function. The estimated number of button clicks, for the three presentation methods, is summarized in Table 15. Results of the analysis of model effects showed that there was evidence of a significant presentation method effect (Wald Chi-
Square(2, N=216) = 8.18, p-value = 0.017), thus there were significant differences in the number of button clicks for the three different presentation methods. The estimated mean for the number of button clicks for the TTO method was 24.9 and 24.0 clicks greater than for the TTS method and TSO method, respectively. The difference between the TTS method and TSO method was only 0.9 clicks. Examining pairwise contrasts for the different presentation method: the TTO method was significantly different than the TTS method (p = 0.008) but not the TSO method (p=0.074). There was also no significant different between the TTS and TSO methods (p=0.924). Thus, we can only say that the TTO method was significantly worse than the TTS method in terms of the number of button clicks needed to obtain word feedback about the features. There was also a significant main effect of Diagram Presentation Order (Wald Chi-Square(2, N=216) = 19.2, p-value < 0.001), Method x Diagram Type (Wald Chi Square(2, N=216)=27.2, p-value < 0.001), Diagram Type x Diagrams (Wald Chi Square(2, N=216)=8.47, p-value =0.014) and Method x Diagram Type x Diagrams (Wald Chi Square(4, N=216)=10.7, p-value = 0.031). The effect of diagram presentation order was indicative of the fact that learning occurred across trials and so the number of clicks needed decreased with the increasing number of diagrams presented (i.e., means in order were 91.0 with SE=6.04, 82.4 with SE= 4.90 and 73.6 with SE=4.74 clicks).

7.2.4. CONFIDENCE
For rating their confidence in the presentation methods, participants used a scale from 1 to 10, where 1 indicated they were very confident and 10 indicated that they were very unconfident. The model of confidence ratings was modeled using GEEs assuming a normal distribution for the response variable and an Identity link function. The estimated confidence, for the three presentation methods, is summarized in Table 16. Results of the analysis of model effects showed that there was evidence of a significant presentation method effect (Wald Chi-Square(2, N=216) = 27.4, p-value < 0.001), thus there were significant differences in the confidence for the three different presentation methods. The estimate mean confidence rating for the TSO method was 1.29 and 1.87 points lower (i.e., more confident) than the TTS method and TTO methods, respectively. The rating was also lower for the TTS method as compared to the TTO method (difference =0.58 points). Examining pairwise contrasts for the different presentation methods, all comparisons were significantly different: TTO to TTS, p = 0.031, TTO to TSO, p < 0.001 and TTS to TSO, p < 0.001. Thus, we can say that participants had most confidence in the TSO method, followed by the TTS method, and, finally, the TTO method.

7.2.5. DIFFICULTY

For rating the difficulty of the presentation methods, participants used a scale from 1 to 10, where 1 indicated that the method was very easy and 10 indicated that the method was very difficult. The model of the difficulty rating was modeled using GEEs assuming a normal distribution for the response variable and an Identity link function. The estimated
difficulty for the three presentation methods is summarized in Table 16. Results of the analysis of model effects showed that there was evidence of a significant presentation method effect ($\text{Wald Chi-Square (2, N=216) = 37.5, } p\text{-value < 0.001}$), thus there were significant differences in the confidence for the three different presentation methods. There was also evidence of a significant Diagram Type by Diagram Presentation Order effect ($\text{Wald Chi-Square (2, N=216) = 8.68, } p = 0.013$). For the presentation methods, the estimate mean difficulty rating for the TSO method was 1.25 and 1.15 points lower (i.e., less difficulty) than the TTS method and TTO method, respectively. The rating was also lower for the TTS method as compared to the TTO method (difference =0.10 points). Examining pairwise contrasts for the different presentation methods, all comparisons to the TSO method were significantly different: TTS to TSO, $p < 0.001$, TTO to TSO, $p = 0.017$, however the TTS and TTO methods were not significantly different ($p = 0.833$). Thus, we can say that participants found the TSO easiest, and the TTS and TTO methods not significantly different.

7.2.6. SYSTEM USABILITY SCALE SURVEY

The SUS score was determined based on the response of the participants to the questions in the survey. The resulting score could range from 0 (not usable) to 100 (most usable). The SUS score was modeled using GEEs assuming a normal distribution for the response variable and an Identity link function. The estimated mean scores, for the three presentation methods are summarized in Table 16. Results of the analysis of model effects
showed that there was evidence of a significant presentation method effect (Wald Chi-Square (2, N=72) = 27.1, p-value < 0.001), thus there were significant differences in the SUS scores for the three different presentation methods. The estimate mean score for the TSO method was 20 points higher than both the TTS method and the TTO method. There was no difference in the estimated means between the TTS and TTO methods. Examining pairwise contrasts for the different presentation methods, both the TTS and TTO methods were significantly different than the TSO method (p < 0.001). There was no significant difference between the TTS and TTO methods. Thus, we can say that participants preferred the TSO method, but there was no significant difference in the preference for the TTS and TTO methods.
Table 16

Estimates of subjective testing variables used in the study

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Method</th>
<th>Mean</th>
<th>SE</th>
<th>95% Wald CI Lower</th>
<th>95% Wald CI Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence</td>
<td>TTS</td>
<td>4.68</td>
<td>0.39</td>
<td>3.91</td>
<td>5.45</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
<td>4.58</td>
<td>0.26</td>
<td>4.07</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>3.43</td>
<td>0.40</td>
<td>2.66</td>
<td>4.21</td>
</tr>
<tr>
<td>Difficulty</td>
<td>TTS</td>
<td>4.49</td>
<td>0.33</td>
<td>3.84</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
<td>5.08</td>
<td>0.30</td>
<td>4.50</td>
<td>5.67</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>3.21</td>
<td>0.33</td>
<td>2.56</td>
<td>3.86</td>
</tr>
<tr>
<td>SUS</td>
<td>TTS</td>
<td>54.38</td>
<td>5.24</td>
<td>44.11</td>
<td>64.64</td>
</tr>
<tr>
<td></td>
<td>TTO</td>
<td>54.38</td>
<td>3.70</td>
<td>47.12</td>
<td>61.63</td>
</tr>
<tr>
<td></td>
<td>TSO</td>
<td>74.38</td>
<td>4.24</td>
<td>66.06</td>
<td>82.69</td>
</tr>
</tbody>
</table>

* CI= Confidence Interval, SE= Standard Error

7.2.7. RANKINGS

For the last task of rating the preference of the testing methods, only 9 participants responded. Using the related-samples Wilcoxon Signed Rank test, we examined the rankings for statistical significance. The ranking of the TSO method was statistically different from both the TTS (p=0.018) and the TTO (p = 0.020) methods, and was the
method preferred by the users. The TTS and TTO methods were found not to be significantly different (p = 0.803).

7.3. OBSERVATIONS AND COMMENTS

We observed that all participants used a mixed exploration strategy of horizontal, vertical and random movements for detecting the different features present on the map. All participants used only a single hand to hold the device, except P5 and P10 who used two hands. Both of these participants used the left index finger to press Button 3 and the right hand index finger for obtaining tactile feedback on day 1. On day 2, P5 used only a single hand, whereas P10 kept changing between a single and two hands. Another thing that we noticed was that a few participants (P5, P6, P7 and P10) relied heavily on using Button 3 to get auditory text feedback about the name of the feature rather than feeling the tactile feedback. During casual discussion, P6 and P7 mentioned they were heavy text to speech application (JAWS; Freedom Scientific Inc., 2012) users and this was the reason why they relied on the audio text feedback more than the tactile/sonification feedback. However, we did not notice any difference in the performance of P5, P7 and P10 as compared to other individuals for the entire testing variables. Only one participant P6, was not able to complete the entire experiment. During the second day of testing, for their last testing method TTS, P6 got really frustrated with the testing method and decided to stop the experiment.
Table 17

Participants comments about the testing methods, not paraphrased.

<table>
<thead>
<tr>
<th>Participants</th>
<th>TSO</th>
<th>TTS</th>
<th>TTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&quot;It was easier to use, vibration and sound was the best combination&quot;</td>
<td>&quot;Features were easier to find, as only a few things were present on diagram&quot;</td>
<td>&quot;Features were very difficult to find and differentiate, everything felt the same&quot;</td>
</tr>
<tr>
<td>3</td>
<td>&quot;I leaned the combination fast, very easy to use&quot;</td>
<td>&quot;Once I find something, when I switch and come back I cannot find the same thing&quot;</td>
<td>&quot;You can feel two different sensation and was able to identify them&quot;</td>
</tr>
<tr>
<td>4</td>
<td>&quot;I enjoyed using this method&quot;</td>
<td>&quot;It was good not overloaded as few things were present. I like the idea of one diagram at a time than both&quot;</td>
<td>&quot;I prefer this last, it was difficult to differentiate and too much was present on the same diagram&quot;</td>
</tr>
<tr>
<td>9</td>
<td>&quot;I like this better than TTO&quot;</td>
<td>&quot;I don’t like this method for the floor map, but like it for geographic map&quot;</td>
<td>&quot;This was hard to use&quot;</td>
</tr>
<tr>
<td>12</td>
<td>&quot;I like audio better&quot;</td>
<td>&quot;I like this as I can find&quot;</td>
<td>&quot;I like this system,&quot;</td>
</tr>
</tbody>
</table>
than vibration. I can apply this and get better with experience" one feature, switch to another and just match" easiest thing to use"

7.4. DISCUSSION

The main purpose of this experiment was to compare three different potential methods for accessing overlapping sets of features presented in a graphical diagram when vision is not available, such as to provide access to individuals who are blind and visually impaired. Both auditory feedback (through the computer’s speakers) and tactile feedback (through a refreshable haptic display, Owen et al., 2009) were used, with the haptic display device keeping track of absolute position on the virtual map for both (absolute position tracking as opposed to relative position tracking, such as with an optical mouse, is needed to accurately perceive locations (Rastogi and Pawluk, 2010a). Three presentation methods; tactile-tactile toggle (TTS), tactile-tactile overlap (TTO) and tactile-sonification overlap (TSO) were considered and tested on two different types of diagrams, multi-feature set geographic maps and multi-floor maps of a train station. In retrospect, for completion, we should have included sonification-sonification toggle and sonification-sonification overlap to study the interaction between the sensory domain used and the presentation (toggle or overlap) used. However, we chose only three methods for
tractability: we expect that audition would likely have similar performance to the choice of toggle/overlap as the tactile domain.

The selection of the feedback parameters used for either touch or audition potential could affect the performance of the above three methods. We tried to choose feature sets that were the most salient for each method. For representing one dimension of the tactile or auditory feedback (matched to one set of features), logarithmically increasing frequencies was chosen (although with different base points) for its high saliency in both domains. For the TTO method it was reasoned from previous work and our initial pilot testing that the most effective second dimension (matched to the other set of features) would be tactile “animations”. However, we performed a preliminary study to explore the issue for the TTS and TSO methods. Taking what we believed to be the most different salient dimensions (temporal frequency and animations), we examined their effect on performance. As we found no significant difference despite the wide variation in how the second dimension was presented, albeit with a trend in favor of tactile temporal frequency, we chose tactile temporal frequency for the second parameter.

As hypothesized, we found that using two different modalities, in accordance with cognitive load theory, was the most effective method for providing access to two different sets of features on the same diagram. We found that for all the testing variables, both objective and subjective, that the TSO method was either significantly better or comparable to the best of the other methods (i.e., TTO and TTS). The number of correct responses for the TSO method was much greater than for the TTO and TTS methods, by 17% and 21%. This method was also found to be the one which users had the most
confidence in, found easiest to use and gave a usability rating 20% higher than the other methods. This inference was also supported by the comments of the participants (P2, P3, P4, P9, P12), as shown in Table 17. Surprisingly the response time and the number of button clicks used to indicate what a feature(s) was were comparable to the TTS method. This was unexpected as the TTS method was expected to be more cumbersome than the other methods since it required time to switch between the two different diagrams and memory to remember where the features were. In addition, we had thought that using the two different domains would make it easier to remember the matching of features to tactile/auditory stimuli and be, subsequently, faster. However, this was apparently not the case.

However, in some situations there are some difficulties in using the TSO method. First, it prevents access to individuals who are deaf-blind. Second, it could be difficult to use in public environments where there is high noise (e.g., a busy train station). Although headphones can be used, it prevents hearing environmental sounds (such as when navigating with a white cane or listening to colleagues in an office). These limitations have to be weighed against performance with each method, which was 17-21% greater for the TSO method than the other methods. However, for someone completely deaf-blind, using tactile feedback only is the only solution.

For the two tactile only methods, TTO and TTS, although there was no statistical difference in the number of correct response, perceived difficulty and usability between the methods, there was in terms of response time, button clicks and confidence. The response time was approximately 50% greater for the TTO method and the number of button clicks
approximately 34% greater. Also, contrary to our expectations, only one participant (P3) mentioned the TTS method as difficult to keep track of information when switching features sets. All other participants, based on their comments, seemed to prefer the TTS method compared to the TTO (although this was not true when examining the usability, difficulty or ranking of the two methods). These results suggest that, in fact, the TTS method should be used if only tactile feedback can be used. One reason for this result maybe that, despite, choosing very different tactile dimensions for the TTO case, it was still difficult to distinguish between the two: this can be seen by the increase in the number of button clicks needed. The second reason may be that tactile diagrams are easily “cluttered” (Edman, 1992) and it may be difficult to remember the shapes of areas as geometric information can only be processed in series by the tactile sense (Lederman et al., 1990).

One concern, though, with using the TTS method is that there is a significant performance limitation (17%) as compared to the TSO method (neither of which is close to 100%). One possible improvement to investigate in the future is based on the fact those individuals who are deaf-blind have different degrees of impairment: it is possible that designing displays to take advantage of residual vision or hearing may improve performance. Also, it is not clear in the best case (presumably sighted individuals with vision) how high performance would be: we could not study visual performance with the same participants as all were visually impaired. One direction that we are also interested in investigating in the future is whether the use of auditory and tactile feedback for some
dimensions can improve performance and/or response time for visual displays with several overlapping feature sets that need to be compared together.

In terms of limitations of our study, one set of limitations arises from the restricted set of diagrams and questions that were used in the experiment. This was done for two reasons: (1) to make the objective of what the participants had to do easy to understand, and (2) to keep the time of the experiment tractable. It is possible that with more intricate questions and subtle distinctions between whether features overlap each other that the TTO method may be preferable to the TTS. Further testing, using diagrams and questions drawn from actual lesson plans and such is warranted. Another limitation in our study is that we investigated only three different rendering parameters: tactile temporal frequency, tactile animations and auditory temporal frequency. These were chosen, based on the results of others and our exploratory work, as the most differentiable as well as salient. It is possible that different rendering parameters may produce different results. However, again we limited our study to ensure its tractability and chose parameters comparable in saliency though we believe the difficulty in saliency for the TTO method is inherent in the method and not the parameters chosen. To validate this claim, a more comprehensive study using a wider variety of rendering parameters could be performed.
8. CONCLUSION

An increasing amount of information used in our everyday lives is being presented graphically, which has created challenges for individuals who are blind or visually impaired to independently access this information, as required for their self sufficiency. Additionally, much of this information is now being presented in some form of electronic media, such as over the internet or through electronic devices, requiring access in more dynamic environments. In the introduction, we discussed one group of devices that can be used to access such information, namely refreshable haptic displays. Although these devices have several advantages over their physical counter parts, they are still not widely accepted by individuals who are blind and visually impaired. We suggested that the usability of these displays can be further improved by developing special computer applications, keeping in mind the needs of haptics as compared to vision.

In this study, we proposed to develop an automated haptic user interface (AHUI) that consists of haptic computer tools that perform magnification and simplification to provide access to the entire visual information in a manageable fashion. This was done by allowing users to manipulate the diagram to compensate for the inherent limitations of the haptic system based on the current and changing needs of the user.
Towards the first goal of developing a magnification tool, we were able to successfully develop an improved zooming algorithm that took into account both the poorer spatial resolution of touch and the serial processing of geometric information. From the series of experiments we performed, we were able to effectively test the need and advantages of our proposed zooming algorithm against other visual zooming algorithm. We found that our proposed zooming algorithm performed significantly better for the testing tasks. Subjective comments from individuals who were blind or visually impaired also supported this. Hence, we believe we were able to achieve our proposed goal. However, we believe there is still room for improvements in the algorithm and more thorough testing for its robustness is needed before the final implementation of the algorithm in an AHUI.

Towards the second goal of developing a simplification tool, we were able to prove that allowing the users to perform dynamic boundary and contextual simplification significantly improved the performance of participants. In this study we did not actually implement the automated simplification, however, in future, we would like to investigate the methods that we proposed in Chapter 2 towards the development of this automated simplification tool. In the last study we were able to identify the best presentation modalities, tactile temporal vibrations, tactile spatial animations and auditory tones that could be used to represent two set of features on diagrams that need to be compared. We found that tactile-auditory is the best presentation method that could be used for presentation overlaying information to individuals who are blind or visually impaired.
However for individuals who are deaf blind, the tactile-tactile toggle would be the best method.
9. ACKNOWLEDGEMENT

This work was supported by NSF grant # 0712936 awarded to Dr. Dianne T.V. Pawluk.
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