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Assistive Technologies for Independent Navigation for People with Blindness

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Assistive Technologies for Independent Navigation for People with Blindness

by

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Dedication

I would like to dedicate this dissertation to my family and friends. A special hand of gratitude to my parents, Ken and Rhoda Kaplan for their encouragement and sacrifices for educating and preparing me for the future. I am also extremely grateful to my siblings David, Rachel, and Amy for being by my side always. Thank you to my second parents Paul and Hilary Cherry for always being ready to provide input. My grandparents Harvey and Helen Sherer, we have come along way and will continue your legacy of love and caring. An additional thank you to my wife’s family for helping us during this process. And last but certainly not least, I am forever thankful to my wife Andrea and daughters Hyla and Kinsey for their love and inspiration. I am proud of you Hyla and Kinsey and will be there to love and support you just like you have been there for me.

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Abstract

The necessity for individuals to navigate from location to location is essential to daily life. The majority of humans use sight as the main source for determining how to move through their environment. However, there is a large population of people who are either blind or living with low vision. Based on a 2017 National Health Survey there are around 27 million adult Americans that have experienced vision loss (National Center for Health Statistics, 2017). According to the Eye Diseases Prevalence Research Group there are 3.4 million Americans 40 years and older that are legally blind or visually impaired (EDPRG, 2004). There are very limited resources for this population, especially for when it comes to tools for spatial and navigational understand of environments.

Maps and building layouts are generally available as two-dimensional images, which presents problems for blind and visually impaired persons. For example, maps, such as those provided on placards and kiosks at various locations are typically only provided as two-dimensional schematic of the area. In some instances, these two-dimensional maps may also include critical information such as evacuation routes in case of an emergency. Furthermore, while text may be presented on these maps as braille or raised lettering, this only provides textual information to the user, and does not fully and effectively describe the physical environment or navigational routes. Accordingly, there is a need to provide a resource that enables people with blindness or low vision to obtain the same mapping information as sighted individuals. One solution that addresses this need is based on tactile maps. However, it is important to create

tactile maps with the appropriate representations and indicators to allow for easier access and understanding of spatial information for individuals living with blindness or low vision.

Wide availability of 3D-printers has made possible simple creation of tactile maps. However, typical tactile maps are often done by direct translation of 2D maps made for sighted individuals. These maps, however, are not focused on better readability and functionality and do not consider the requirements of a person with blindness or low vision. By studying how people with blindness or visually impairments perceive and use tactile sensation to learn about their surroundings we can provide more effective solutions to the development and design of the tactile maps. We also leverage newer production techniques using consumer grade 3D-printers, which allows for the development and testing of 3-dimensional tactile elements to be incorporated in a map. 3D-printing technology also allows for a greater number of tactile variants, than other traditional methods, and enables rapid prototyping for quicker user testing and iterative development.

The work in this dissertation presents a user-based iterative process for the development of new encoding rules which optimize map creation and functionality. In terms of user perception and comprehension this work demonstrates the 3D-printed tactile map developed enable people with blindness and low vision to obtain an improved understanding of environments, and an increase in mobility and independence. Additionally, this work presents deeper understanding in the spatial and tactual perception of blind and visually impaired people.

In this dissertation, first, we describe the various types of maps that were developed and tested by blind and low vision users. Then we explain how the user testing and feedback lead to the creation of a novel tactile encoding system. We further evaluate effectiveness of the encoding system for communicating spatial and navigational information, and how it provides a valuable

resource for the users. We also present a tactile encoding system focused specifically on interior maps along with an analysis of the numerous encodings and encoding parameters tested. The final encodings system provides a novel approach for the creation of optimized interior tactile maps.

Chapter 1: Introduction

1.1 Motivation

Across the globe there are 1.3 billion people with some form of visual impairment. 217 million individuals have moderate to severe vision impairment, while 36 million people are living with blindness (WHO, 2018). An impairment is a physical, mental, or physiological loss, abnormality or injury that cause a limitation in one or more major life functions (Cavender et al., 2008). A person, in the United States, is considered legally blind if they have vision that cannot be corrected to better than 20/200, or if they have 20 degrees or less of visual field remaining (American Optometric Association, 2019). The term "low vision" refers to uncorrectable vision loss and is the lack of vision functionality, rather than [numerical] test (Massof & Lidoff, 2001). Many professionals diagnose individuals with "low vision" if they have permanently reduced vision that cannot be corrected with glasses, contact lenses, medicine, or surgery (American Foundation for the Blind, 2019).

A person's sense of vision is paramount for their ability to safely navigate the environment around them. A lack of vision hinders a person's spatial awareness and limits their knowledge of the environment. These limitations can also have a negative effect on a person's daily life, as well as educational and recreational opportunities. Additional negative outcomes can be poor health, social isolation, and depression (Popescu, et al., 2012). As a result, they have limited access to many important tools, jobs and resources available to sighted individuals. Consequently, many advocates and researchers emphasize the need for equal access to all those resources for people with impairments (Sheppard & Aldrich, 2001; Siekierska et al., 2003).

The National Health Interview Survey (NHIS) showed that an estimated 23.7 million adult Americans reported they either "have trouble" seeing, even when wearing glasses or contact lenses, or that they are blind. The number of Americans who have visual impairments or are blind is increasing and is projected to double by 2050 (Varma, et al., 2016). People in the United States are living longer as a result the population of individuals with vision loss or blindness is growing. Many of these individuals are living without the support of caregivers. The increase in the number of people needing support coupled with the shortage of caregivers means that this population will have to become more independent to meet the challenges associated with everyday activities (Teutsch et al., 2016). This is especially true in terms of independent mobility, orientation, and navigation when travelling from one location to another (Lobben & Lawrence, 2012). Mobility presents enormous concerns for this population and is linked to unsafe travel leading to falls resulting in physical injury. Navigation through unknown spaces presents problems for this population as environments and travel routes are complex, often with many spatial factors that need to be addressed such as physical barriers and travel routes. Additionally, there are constant changes that can occur without warning due to construction, closures, and other reasons. This research aims to provide a solution that may lead to a better quality of life for individuals living with blindness and low vision by providing them with resources to improve their understanding of environments.

The types of resources available for people with blindness and low vision has not change much over the past century. The most common and widely used tactile system is Braille, which was originally created in the early 1800’s (American Foundation for the Blind, 2019). Tactile maps used to teach geography to both sighted and blind students were produced on relief paper in the early nineteenth century (Levy, 2015). However, these maps mainly relied on braille, and lacked feature detail due to limited tactile embossing. Tactile maps for navigation and mobility did not appear until the early 1900's and still relied on Braille for delivering navigational and spatial information.

Some technological advances in Geospatial Positioning Systems (GPS), and audio-based hardware and software provide just-in-time information. However, these types of technologies don't enable the user to freely explore and build meaningful relationships from the resource that allows them to effectively understand the locations of interest to them. These turn-by-turn technologies are passive in nature as users have to rely on the device to deliver them information (Lobben & Lawrence, 2012). It has also been shown that these types of devices inhibit navigational skill development and spatial awareness (Parush et al., 2007; Ishikawa et al., 2008). Another useful approach would be navigation with a help of tactile maps based on relief graphics. Tactual maps help individuals with blindness and visual impairments to better understand an environment before direct navigation through the space. It has also been shown that tactile maps improve cognitive awareness, wayfinding, and spatial knowledge (Perkins, 2002). However, the majority of research on tactile maps is focused on either comparing production methods or evaluating a single symbol set, often outside of the context of a map. These studies are typically done as individual tests, and not as a series of tests focused on refinement, such as the work presented here.

Furthermore, there are no standards in place for building maps with proper tactile representations of physical objects that provide people with blindness and low vision spatial information (Brittell et al., 2018). There have been a few attempts to tactile standardize symbology such as the Nottingham kit developed for exterior urban environments in the early 1970's (James & Armstrong, 1976; Perkins, 2002) provided orientation and mobility symbols as lead strips that were set to be used to produce plastic-formed maps. In the late 1980's the Nottigham kit was updated to the Euro Town Kit, which consisted of 28 tactile symbols, made from the same materials, for urban tactile mapping (Laufenberg, 1988; Edman, 1992). Kits similar to these are limited in scope and can be costly to purchase and produce (Lobben & Lawrence, 2012). Other work has been geared towards a broader view of developing tactile guidelines as opposed to focused symbol standardization (Perkins, 2002). Generally, tactile maps when used are created ad hoc and/or with the use of traditional methods such as embossers, braille, and microcapsule paper or tactile image enhancer. These traditional production methods take longer periods of time to produce and are often inaccurate since changes to the space typically occur before the maps have been provided, rendering them ineffective when received by the user. These production methods also do not fully utilize z-axis (height) reducing the amount of tactile contrast that can be applied to the map display (Jehoel et al., 2005). Tactile parameters, especially for maps, need to effectively use the sense of touch by providing variations in tactual properties to communicate navigation and spatial information to people with blindness or low vision. Previous research has been shown that by applying contrasting tactual properties to the symbol set available on a map display it will provide better discriminating of map elements for the user (Gardiner & Perkins, 2002; Nolan & Morris, 1971). However, research and discussion on tactile parameters and standardization continues to be explored.

New technology such as 3D-printing has the potential to offer a faster and more accessible processes for the production of tactile maps. 3D-printing has also been shown to be more cost and time-effective than out-sourcing to embosser services (Cavanaugh & Eastham, 2019). However, access to 3D-printing alone is not enough to produce an effective tactile map. Map development should adhere to a set of rules that utilize consistent standards for providing information tactually with the users' needs in mind. Producing tactile components for people with blindness and low vision requires proficient understanding of how tactual information is perceived and interpreted by individuals with blindness or low vision. Knowledge about how this user group identifies, reads, and connects the tactual data provided in the map, to meaningful spatial orientation, mobility, and navigation information is essential. The user feedback is vital and must be considered in the development process. There are currently no rules or set of symbols that are standardized for the creation of a tactile map (Perkins, 2002). A very limited amount of research has been conducted on the tactile encodings for maps. Further, exploring how to create and deliver an optimized system for communicating spatial and navigational information through tactile elements presented on maps has not been researched. The lack of tactile rules for map creation provides additional challenges for the user when learning to read maps that are available. Since maps can be created anyway the developer wants to build them the user is asked to learn many styles and types of tactile properties used for maps that are varied based on how they were created. The type of production method, and materials also different greatly further hindering map use. The lack of standard guidelines for tactile symbology and limited accessibility results in maps that are too difficult for the user to read and comprehend, poorly created maps, or no maps being provided at all to the user. Furthermore, variations in map symbology requires the user to learn new symbol sets each time they use a map. As opposed to maps for sighted people, where standardization of symbols improves map cognition allowing the user to more efficiently learn and read map routes (Lobben & Lawrence, 2012). A large number of tactile graphics offered also use visual principles of design in an effort to communicate information tactually to people with blindness and low vision. When maps are produced in this manner 2D images are merely raised adding a relief 2.5D property. This may work with simple illustrations of shapes, however, complex graphics, such as maps, produced through this method are not easily read through touch sense and require alternative tactile, haptic, and/or audio accommodations for users to interpret and understand (Thompson & Chronicle, 2006). Additionally, maps are aimed at communicating multiple features and structures, as such, cartographic techniques might be used to provide more context for the user to read and understand (Rice et al., 2005; Holloway et al., 2018). However, cartographic pictorial representations developed for sighted individuals may not be effective for tactile maps for orientation and mobility. Various studies show that visual information may not translate correctly when perceived tactually, especially by those that are blind and visually impaired (Ojala et al., 2016). Additionally, we reviewed traditional approaches to map design from a visual perspective where cartographers design maps often determining what information to omit from the design. However, while designing tactile maps we must consider, from a user perspective, what information to include. Furthermore, we must decide how to represent this information tactually. This approach to map making is in opposition to traditional cartography (Rowell & Ungar, 2003).

The work presented in this thesis serves as a resource for providing tactile encodings and map design algorithms that have been developed through a user testing iterative process. This study was enabled by availability of rapid prototyping technology that allows us to quickly produce and evaluate symbols and combinations of symbols integrated in tactile maps with the target user. In order to provide an optimal solution for the creation of tactile maps collecting and analyzing data from this user population is vital. Additionally, the data collected through this work will guiding the parameters of tactile maps developed that are necessary for effective map reading and comprehension by people living with blindness and low vision.

1.2 Contributions

The main contributions presented in this dissertation are summarized as follows:

1. The development and evaluation of a novel tactile encoding system for creation of tactile maps based on iterative user feedback and optimized for efficient information delivery to blind and visually impaired users.
2. The development of the guidelines for integration of encodings on 3D-printed tactile interior maps with optimized and effective delivery of tactile information. The resulting abstractions, encodings and algorithms can be applied to the future standardization of tactile map design.
3. The development and practice of tactile map design for people with blindness and low vision to enable safe navigation of interior environments. This work will also provide us with a better understanding of how blind and visually impaired people receive, process, and use tactile content for mobility and spatial orientation. Additionally, this research will offer valuable information about how to work with this population within a design space.
4. A detailed analysis of the unique needs and challenges of blind and visually impaired individuals as it relates to the design and development of tactile devices for communicating spatial and navigational information is also presented. This work reveals how these users interpret and access tactile data using 3D-printed map displays for safe and accurate mobility and orientation. Through this work we lay a scientific foundation under future assistive technologies and interventions that are most focused on satisfying unique needs of this population. This contribution will also provide mechanisms that will allow these individuals to be more confident and independent with navigation of spaces. This work will also help mobility and orientation instructors, caregivers, and teachers by providing a system for the creation of tools that will enable them to better understand the

requirements to effectively delivery tactile spatial maps and graphics to people with blindness and visual impairments.

1.3 Dissertation Organization

This thesis contains eight chapters, as follows, including the present one.

1. Chapter Two presents a literature review and theoretical background for research and related work done in the field of assistive technology and tactile devices for people with blindness and low vision.
2. Chapter Three explores the design and development process with the end-user, people with blindness and visual impairments.
3. Chapter Four discusses the design, development, and testing of the first generation of tactile maps that we created.
4. Chapter Five goes through the design, development, and user testing of the optimized tactile map encoding system.
5. Chapter Six presents a study comparing two types of tactile encoding systems, unique and additive.
6. Chapter Seven introduces a prototype of the Tactile Map Creator application, user-testing of the application, an analysis of the audio-haptic and 3D-printable maps from the application, and future developments.
7. Chapter Eight gives a summary and conclusion of this dissertation.

Even though there have been numerous research studies about methods for providing tactile information to this user group, little has changed in terms of access and standardization of tactual representation for visual-spatial and navigational information, especially for producing and providing tactile maps. There are several reasons for this, including: the various needs such as language, cultural, educational requirements, and the subjectivity of various user likes and dislikes. There are also manufacturing limitations, and cost and accessibility challenges for disadvantaged users. Additionally, the development of an optimized tactile encoding solution to effectively communicate visual-spatial and navigational components to the end-user has not been studied or established in terms of a user-centered approach for both caregivers or providers, map creators, and end-users, people with blindness. To do this requires extensive testing and feedback with end-users while iteratively determining the spatial elements and features that need to be included and excluded, the types and styles of the tactile map encodings, map size and spacing requirements, and an accessible production method. This research aims to provide a solution for the development of optimized tactile encodings for tactile maps that can be used to build an understanding, and possible for users to plan their travel strategy for interior spaces prior to visiting the location.

Chapter 2: Literature Review and Background

In this chapter, various tactile graphics, development of tactile maps, tactile literacy, and available technologies for blind and low vision users are discussed. An introduction on methods of generating 3D models, and the use of 3D-printing to produce tactile graphics and maps is presented.

2.1 Introduction

Visual graphics such as charts and maps use images to represent elements that communicate information through our sense of sight. It is with our sight that we perceive these images which are then translated and read by our brain to form meaning and understanding. This is not the case, however, for individuals that have limited or no vision. When sight is not an option these individuals rely on touch, especially for daily activities such as navigation, and reading. Standards for information delivery to people with blindness or visual impairments, however, is limited to text with the use of either braille or raised text, and some pictorial signage, for example raised gender specific restroom signage.

Tactile graphics are physical tools used by blind and visually impaired for learning through the sense of touch. Tactile graphics often display non-textual content such as images, graphs, diagrams, and charts (Staff, 2018). Tactile maps are a type of tactual graphic used to describe visual, navigational, and spatial information for both interior and exterior locations (Mooney, 2016). Tactile graphics use raised surfaces to represent and convey information to visually impaired persons. In general, tactile maps are used as educational tools, and in orientation and mobility (O&M) training (Rowell & Ungar, 2003). Many research studies have shown that the use of tactile maps by blind and visually impaired have improved their ability to build mental representations of actual physical environments (Blades et al., 1999). These maps have been shown to be an important learning tool for children as studies have shown improved independence from the use of tactile maps (Arnott, 2018). Various studies have shown improved user performance in map readability and comprehension when tactile elevations are higher than traditional raised 2.5D production methods (Jehoel et al., 2009). Although, many studies vary on a precise and optimal elevation height for encoding symbols. Research has been shown that individuals could identify shapes at low elevations of .007mm to higher than .5mm (Jehoel at el., 2005). However, few studies have looked at the types and combinations of encodings used together in terms of finding an optimal solution for both map creation and map users. By providing a wider range of tactile textures, and elevations users can more easily identify and build mental models of the map to better understand the locations and objects represented (Lobben & Lawrence, 2012). Therefore, any map for blind and visually impaired should include specific tactile elements representing physical and spatial features that can be easily identified and read. Other parameters such as spacing, size, elevation, and combining symbols need to be considered and optimized. Additionally, work involving volumetric, or 3D tactile shapes has shown improved comprehension and independence in terms of using tactile maps and understanding map features (Gual at el., 2015). Therefore, by studying various 3D tactile encodings properties such as layout, arrangement, and combinations of the encodings we can improve tactile map functionality for both the user and creators (Voigt & Martens, 2006).

2.1.1 Tactile Graphics and Maps for Blind

The earliest tactile graphics were physical 3D elements created from natural objects. Some tactile devices were built by arranging stones or pebbles. Clay tokens dating back to 5500

BC are some of the earliest forms of tactile data visualizations (Schmandt-Besserat, 1999). Tactile maps have been used for centuries. Some map examples from the 1800's show city layouts, and were made of thick board, and cloth (Arnott, 2018).

There has been little modernization of tools and methods for communicating spatial and structural information to blind and visually impaired individuals through tactile properties. The development of standard tactile encodings has also been generalized and limited to basic elements such as the use of points and lines. Various guidelines and suggestions have been given with respect to the creation on tactile maps, whether handmade or by machine, however, they are based on conventional methods of production.

2.2 Devices and Technology for Blind and Visually Impaired Users

There are numerous devices that have been invented that are used in to produce tactile resources for people with blindness and visual impairments. The two main technologies thermoforming and embossing have been in existence since the late 1940's and mid 1800's respectively (McGinnity at el., 2004). Common methods of tactile map creation through embossing or raised paper, vacuum-forming, microcapsule, or foam ink-based systems are widely used for hard-copying tactile graphics production (Challis at el., 2001; Perkins, 2002). Raised or microcapsule paper maps are more limited than 3D maps in terms of providing a range of elevation and textural capabilities. The features produced on Swell paper are generally raised by approximately 0.5 mm, and Braille embossers provide dots at elevations of 0.25 to 1.0 mm (Gill & Silver, 2005). Embossing and microcapsule methods of production for tactile maps and graphics also reduces the number of symbols that can be applied to the same display (Edman, 1992) because of their limited output process (Figure 2.1). Other devices such as braille-embossers allow users to take flat black and white 2D print images of braille and have it raised to various heights creating tactile braille copies. One can also print or copy a black and white image on "Swellpaper". This is a special thermoform paper that is placed in a radiant heater and obtains a tactile copy when the black areas swell and expand. However, these methods merely convert a 2D graphic or image to a 2.5D raised version using color information. Using this conversion technique does not produce or take into consideration effective tactile representations of the objects that are suitable for blind and low visions users to read and understand through touch.

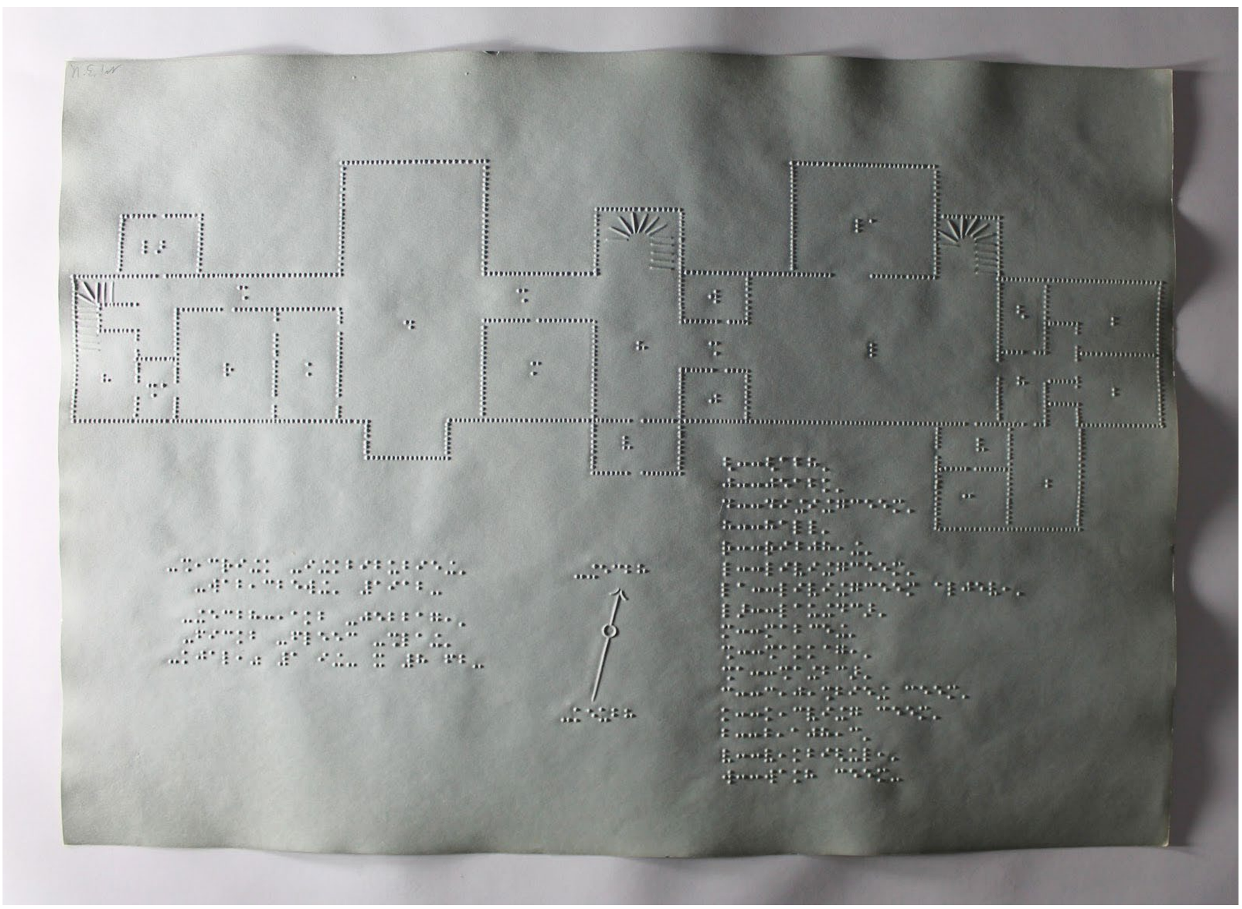


Figure 2.1 A microcapsule floor plan of residential cottage at the Perkins School for the Blind. Dotted lines with braille notation. “Courtesy of Perkins School for the Blind Archives”.

Traditional map and image making methods have been updated with new production technology, however, new encoding design for delivering visual information to blind and visually impaired users have not been created or updated. The updated production process has merely continued to make traditional methods, such as text, braille, and raised images easier or more efficient to produce with new developments in production hardware. Furthermore, these traditional technologies are not only limited in functionality but have additional costs associated with them. For example, embossers are expensive ranging in price from $500.00 to more than $20,000.00. Microcapsule or Swell paper can cost an average of $150.00 for one-hundred sheets, are limited to one height elevation for all components, and deteriorate quickly when used (Teiresias Centre, 2018). There are some companies that offer services to convert books to braille, however, they are expensive, can take months or even years to produce, and provide no improvement in tactual properties since they use the same traditional production methods mentioned above. Additionally, if there are images associated with the text, they are either omitted or produced poorly through embossing, and usually accrue additional cost.

Figure 2.2 Traditional tactile map of Boston that has been mounted onto a thick board, cut out, and glued onto a green colored board. Streets, wharves, and some landmarks stand above the background, circa 1830. Courtesy of Perkins School for the Blind.

2.2.1 Modern Assistive Technologies

Computer applications such as audio screen reading software, speech synthesizers and real-time touch braille displays have been introduced in recent years. However, audio text readers are limited largely to unformatted text, and braille displays only display text information (Bulatov & Gardner, 1998). These types of readers only attempt to translate text and do not describe images. Other technologies have been incorporated to help improve accessibility such as computer-based audio screen readers with the use of the alternative or "alt" tag to describe images on web pages. However, the use of the "alt" feature must be manual implemented and is typically not done in such a way that the images are easily understood by the end-user and are often left out completely. Audio readers are also not customizable for individual users and do not allow for exploration of the image features. Therefore, audio readers do not provide adequate attributes for users to gain an understand of visual-spatial data. There have been recent studies involving the conversion of 2D data graphs and visualizations into audio text tables, some using automated machine learning technologies (Choi at el., 2019). Text to speech tools also present challenges in verbally describing visual content in a manner that can be internalized and understood by individual users. This limitation means that the end-user misses out on the visualization aspects of the image.

Wi-Fi, Bluetooth, range sensing, and wireless network-based technologies have been developed and proposed as alterations to existing mobility aids for the blind (Figure 2.2). The white cane has been used for almost a century to foster independence and safe mobility (Strong, 2009), and is the most common and widely accepted mobility tool. These alterations to the mobility devices typically aim to provide "just-in-time" information using haptic vibration, and/or audio alerts based on the cane or guide dog interaction and location. The adaptations to the standard cane devices have been tried but failed to become embraced by the user population. There are numerous drawbacks and limitations to these types of modifications to the devices because they priorities the immediate space in front of the user and do not provide additional information about the environment that could be vital for the user (Calder, 2009). The audio feedback provided by these devices can be harmful as it can hinder the user's ability to hear natural ambient sounds (Calder, 2010). These devices also require the user to rely solely on the information provided right in front of them or in near proximity in almost real-time, and generally in the direction in which the user is facing. This means that the user does not have the opportunity to learn about the spatial features and navigational routes prior to traveling the space and must rely on the device's capabilities for navigation. Other limiting factors of these devices are that they require proper networking, and other expensive and specialized hardware such as wearable headsets, tracking sensors, and camera that tend to be heavy or cumbersome, and often impede one or more of user's other senses (Figure 2.3). These alterations also tend highlight the user's disability often making them self-conscious (Sachdeva & Suomi, 2013). The user also continues to use their everyday mobility device, (i.e., cane or guide dog), while trying to operate the technology which can contribute to errors in navigation related to cognitive overload. Some live view technologies developed which use a forward-facing camera to stream a blind person's perspective to a visual person remotely are available, however, these systems are still in early adoption stages and require a large amount of overhead as employees need to be available at all times to respond to a user. Additionally, properly trained staff, accessibility, battery life, and privacy issues are challenges concerning these types of alternative technologies. Many of these systems also require user to learn how to use the hardware and software components, further reducing accessibility to users with varying economic and learning needs (Duen, 2007). It has also been stated in similar research work, that a device should ideally be designed to be picked up and used immediately (Burns & Hajdukiewiez, 2004). Systems that use specialized hardware and wireless connections are also costly, and many of them are provided as a subscription service, require special expert setup, and typically link to a data network plan. When network speed, and connection is restricted, or when access to the additional hardware is not available these technologies cannot be used. Bluetooth and Global Positioning Systems (GPS) also rely upon expensive physical augmentation of the environment, expensive sensing equipment, advanced setup, and maintenance, and can only be used in certain environments (Fallah et al., 2012). Furthermore, the ability to expand, scale, and individualized these technologies based on individual user needs is challenging and costly since software is restricted in terms of access to the underline development platform systems. Many of these devices rely on propriety hardware and software components that are developed by smaller companies; therefore, there is a concern regarding technology shelf-life. (Calder, 2010). If the technology does not bleed into mainstream, or has low adoption, or is replaced by newer systems the device may no longer be supported.

2.3 Tactile Literacy

Tactile literacy is a process where touch perception is converted and translated to information based on the tactile elements provided. This includes using the sense of touch to recognize objects, pictures, or other symbols, and using them to communicate (Braille Authority of North America, 2012). This method of data input and output using touch sensation requires the user to have experience using and learning from tactile items. Tactile literacy and fingertip sensitivity is increased and generally refined over time. Tactile items must also be designed appropriately using various physical properties that enable the user to distinguish variations in components representing and/or communicating different information. For the users to receive the appropriate or intended information the tactile properties of the graphic must be produced effectively. A user's hands are typically used to read sensory information accessed by tactile graphics. The sensory perception experience gained from using the tactile graphic is then translated and converted to meaningful concepts, and to external representations that provide comprehension and context.

Figure 2.3 Sonic Pathfinder, a head-mounted pulse-echo sonar system controlled by a microcomputer for out-of-door object detection. Used with permission from Tony Heyes Ph.D.

It is this process which must be repeated efficiently for a tactile graphic to be effective for communicating the information. Tactile graphics rely on a similar process of converting data from physical tactile representations through our sense touch as a mode to both receive and communicate information. However, just because a physical object is provided does not mean it successfully conveys the information. Using Tactile graphics requires a level tactile literacy, and effective tactile graphic usually provide a set of encodings that can be easily understood.

Standards for information delivery for non-sighted individuals is limited to text (braille, or raised text), and some pictorial signage (for example: raised gender specific restroom signs).

There has been no standardization for encoding visual-spatial and navigational information on 3D tactile maps (Chamberlain & Dieng, 2011). Although, there are some guidelines that follow general braille, signage design concepts, and there have been some attempts at symbol standardization for tactile graphics (Cushman & Tabb, 2018). Building an understanding of the tactile literacy process is vital to the creation of appropriate touch-based maps and is the basis for the design and development of our optimized tactile encoding system. If we want to provide blind and low vision individuals with better resources, it is imperative that we as designers gain an understanding of how this user group read and interpret tactile graphics.

Many educational and training facilities build their own tactile graphics using cloth, cardboard, and other craft materials (Hagood, 2021). However, since there has been very limited research into comprehension and content delivery via tactile media, for blind and low vision users, many of these homemade tactile graphics are created with little to no knowledge of appropriate tactile properties that maybe required, and how the tactile components are translated and converted to meaningful information by blind and low vision users. This lack of understanding negatively impacts a user's perception and knowledge to tactually perceive, and mentally read, translate, and learn from tactile graphics. Since limited resources are available orientation and mobility instructors, educators and other providers often do not offer tactile tools, especially maps.

Polly Edman, in his book Tactile Graphics, discusses various types of tactile maps. The types: Mobility Maps, Topological Maps, Orientation Maps, General Reference Maps, all serve a specific purpose in communicating certain information to the user (Edman, 1992). In the design and creation of tactile graphics and maps Edman further identifies three basic tactile components that can be used to differentiate items: point, linear and areal texture symbols (Amick et al., 2002, Edman, 1992). For example, points can be used to represent locations, and lines can be used for displaying direction (Wiener at el., 2010). Although, these design components are basic guidelines for symbols that build off traditional 2D relief displays. More recent studies aimed at comparing volumetric (3D) shapes to conventional flat relief symbols have shown improvements in a blind users' ability to find different symbols more quickly (Gual at el., 2013). Some findings indicate that 3D maps were easier to understand than similar 2D tactile maps due to the higher elevations provided by the 3D shapes (Holloway at el., 2018). Therefore, 3D-printed tactile maps can provide various levels of height, and symbol styles to convey spatial information more effectively than traditional 2.5 maps for the people with blindness.

2.4 Braille, Encodings and Other Symbols

For sighted individuals' text is a visual representation of verbal language, whereas for blind and low vision individual's braille is tactual representation of verbal language. Braille is a code used by people who are blind or visually impaired to read and write. It is the most widely used tactile system for literacy (American Foundation for the Blind, 2019). Braille was developed in the mid eighteen-hundreds by Louis Braille (National Federation of the Blind, 2020). Braille is a tactile code through which letters, numbers, and words are represented using six raised dots in a 2x3 matrix called a cell. In the Braille system dots, dot combinations, and spacing provide a method that enables users to convert the sense of touch response from their fingertips to information that is then translate to text. The elevation, spacing, size, and dot patterns are standard and vital to the legibility of the Braille. There are three levels in English Braille as follows: Grade 1 is a basic one-to-one transcription of printed English. Grade 2 uses the same six dot cell layout to produce patterns that incorporate abbreviations, contractions, and other shorthand. Both, Grade 1 and 2 are standards for braille users. However, the majority of material produced utilizes Grade 2. Grade 3 braille is a more personal form of writing or note taking (Braille, 2020). Braille has remained the only constant system for blind and low vision users that utilizes tactile properties to convey information. Increased cognitive functioning, independence, and self-confidence have all been linked to continued use of braille. However, with advances in technology, such as text to speech and application readers there has been a decrease in braille literacy rates (Lee, 2015). There are also a small number of the blind and visually impaired community that cannot read braille, but instead rely on raised text.

2.5 3D-Printing

Advances in rapid prototyping technology has allowed the 3D-printer to enter the consumer marketplace. With the widespread accessibility and low cost of these printers the demonstration of very sophisticated physical graphics that were previously impossible can be generated. As a result, 3D-printing has become a very useful technology for the delivering innovative individualized and custom educational materials in an 3D tactual format. 3D-printing enables the production of physical objects with varying sizes, textures, and materials enabling the development of tactile maps and graphics that have several advantages compared to traditional manufacturing techniques (Dumitrescu & Tanase, 2016). 3D models can be produced cheaply and quickly from idea to final product. 3D-printing offers designers and developers freedom in creating simple objects to producing highly complex geometries (Jelle at el., 2009). Using 3D computer-aided design (CAD) software the developer can customize and optimize digital models, and model properties, such as height, detail, and texture, and reproduce the digital model as an actual physical object. The type of 3D-printing hardware available to the user determines materials that can be used, and the structural properties of the object that can be produce. Over the past decade 3D-printing has become widely accessible, progressively less expensive, more efficient, and easier to use (Sertogulu at el., 2001). These benefits make 3D-printing an ideal technology for producing tactile graphics.

2.5.1 3D-Printing Introduction

Research has shown that spatial memory and object recognition are both accessed with tactile senses (Xiao, 2011). Since 3D-printing for educational purposes is still in its infancy, there is no general approach to the creation of 3D-printed learning content, especially for visually impaired learners. The information describing an object or phenomenon can be converted into a 3D model through several different approaches, and applications. However, research on the type and style of 3d-printed elements to effectively communicate using touch is limited. Therefore, further research efforts can help improve the process of developing and 3d-printing tactile based content. This is done by combining various elements and 3D models into a single model that can be 3D-printed, and through targeted user testing to measure the delivery of information through tactile perception and acceptance.

3D-printing is a wonderful tool for the delivery of complex spatial or 3-dimensional information to the general population. This technology has been used in multiple settings such as education, product development, and healthcare. The use of 3D-printed models helps learners develop mental representations of abstract concepts (Herman at el., 2006) and thus increases flexibility of thinking and understanding the meaning of abstract ideas. Learning aids that enable students to physically see, touch, or feel a concept provide both a deeper and more satisfying learning experience for a student. The University of South Florida (USF) runs a course in the College of Engineering titled Makercourse. The Makecourse, has been successfully completed by over 200 students. In this course students create 3d models that are 3D-printed and integrated with electronic components, (Park at el., 2018). The ability to 3D-print virtual models provides a more authentic learning experience by allowing students to explore and work within the physical space. A study on the use of 3D-printed anatomical models for undergraduate anatomy was conducted at the University of Sussex, (Smith at el., 2017). The study showed an improvement in learning outcomes with small groups and the use of the 3D-prints as a testing tool for students to properly identifying anatomy. The Department of Geological and Atmospheric Sciences at Iowa State University used 3D-printing to help teach geoscience students about geological topography, (Peterson, 2017). By providing 3D-printed models the students could easily develop a sense of scale from a "touchable topography" (Hasiuk & Harding, 2016). Both Architects and Real Estate agents use 3D-printed models of buildings, homes, and landscapes prior to construction to help them and their clients better visualize both the floorplan and layout of the spaces, (Mackay, 2018). An exhibit at Spain's Prado Museum, created 3D-printed replicas of famous paintings including the Mona Lisa. Blind and low vision people were invited to feel the 3D-printed paintings. It was through the tactile interaction alone that these individuals were able to experience the paintings independently. One low vision visitor said, " I can see light and some colors, but the rest, I use the texture to complete the picture in my mind."(Halliday, 2015). The Tactile Picture Book Project, by Dr. Tom Yeh, from the University of Colorado Boulder uses 3D-printing to provide blind and low vision children tactile replicas of books, (Stangl at el., 2014). Since children typically don't begin learning Braille until age 6, tactile books are crucial for early cognitive development of blind children, (Professional Development and Research Institute on Blindness, 2020). Through the use of emerging digital 3D-printing the tactile books provide a valuable opportunity to rapidly expand the sparse supply of accessible learning materials for individuals with diverse learning needs.

The use of 3D-printing over other methods, such as embossing and Swellpaper, can reduce cost, provide greater accessibility, and produce volumetric shapes that offer more realistic, complex and customized properties (Dumitrescu, 2016).

2.5.2 Types of 3D-Printing

There are a variety of 3D-printing technologies available, however, some of these technologies fall into professional (commercial), or consumer user group categories. The printing technology used is generally determined by the type of output, cost, and expertise associated with the manufacturing or production process. 3D-printers can range in cost from about one hundred dollars for a kit to professional printers costing upwards of millions of dollars. Polymerizations are Stereolithography (SLA and Digital Light Processing (DLP) use a process where a photo-polymer resin in a vat is selectively cured based on the digital model dimensions by a UV light source (Bagheri, 2019), (Figure 2.4, *left*). Selective Laser Sintering (SLS) is a type of Powder Bed Fusion process where a thermal energy source will use the 3D model data to induce fusion between powder particles inside a build volume creating a solid object. Another type of 3D-printing technology is Material Jetting. This process produces droplets of material, typically photopolymers or wax, which are deposited and cured on a build plate when exposed to light. The objects are built up one layer at a time (All3DP, 2021). Drop on Demand (DOD) is a 3D printing technology that uses two ink jets to deposits the build materials, and dissolvable support material. It is similar to other 3D-printing technology where it builds the object layer-by-layer and is generally used for wax casting and mold making. Binder Jetting is another type of 3D-printing, that uses a liquid binding agent to build each layer of a powder, (sand or metal), to form the object (Varotsis, 2021).

Most 3D printers, especially in the consumer market, are Fused Deposition Modeling, (FDM), (Figure 4, *right*). FDM 3D-printing is an additive manufacturing process that generates objects by building up layers of plastic, or other filament materials, using at least one extruder to heat and melt the material. Most of the consumer grade FDM are capable of producing 100μm of resolution. The types of material range from thermoplastic filament (PLA, ABS, PET, TPU) to wood and metal composite filament.

Figure 2.4 Left) a Formlabs Form 2 SLA 3D-printer. Right) a FlashForge Creator Pro FDM 3D-printer. Photographs taken by Howard Kaplan, at the University of South Florida, Advanced Visualization Center 3D-Printing Lab 01.31.2019.

These types of printers move the extruder(s) and or printing plate in three axis left and right, up, and forward and backward following the outer surface of the digital models x,y,z coordinates to draw-out the object in 3-dimensions. FDM printers can have multiple extruders, to print in more than one color or material. There are two main movement types linear and cylindrical. The majority of FDM printers are linear, meaning that the extruder and/or build plate moves up, down, left, and right on straight bars resulting in a stepped positioning and movement process. Cylindrical movement printers typically use three rods with the extruder in the middle. The extruder is moved up, down, right, and left as gears slide, the rods are then moved in unison. In general, the smallest resolution that can be produced by consumer grade FDM printers is fifty microns. Layer heights range from .1mm to .3mm (All3DP, 2021). Consumer grade desktop FDM printers' range in price from $100.00 to $3000.00, with printing output sizes from three inches to three feet. Generally, more expensive printers are larger and have more extruders. Some other features are including touchscreens, automatic plate leveling and wireless capabilities.

Some studies have argued that while FDM printing can be used for tactile map production, the technology is limited in terms of controlling its final surface finish (Voženı´lek & Vondra´kova´, 2015). With cheaper costs of the printer and material, and the rapidly growing user-base the number of materials available for FDM printing has grown, as well as the quality of the printing hardware. Past research has shown that the use of FDM 3D printing of braille and other tactile objects has improved quality in terms of durability and strength over other methods (Zhao at el., 2020).

2.5.3 Methods for Generating 3D Geometry for 3D-Printing

One of the challenging steps in creating tactile graphics using 3D-printing is in the creation of digital models. Digital models are virtual 3D geometries that are typically built from points, curves, and polygons that can be viewed and manipulated in CAD applications. There are many ways to produce 3D models that can be 3D-printed. Creating 3D models, especially, unique custom meshes involves advanced knowledge of the 3D modeling process specifically for 3D-printing and exporting, and an understanding of the 3D-printing application for settings and parameters associated with the 3D-printer being used to print the object. CAD software requires learning complex features and process that can take years to learn especially, when associated with developing 3D meshes. The 3D modeling process requires skills that allow developers to use curves or polygons in a 3D virtual environment to transform 2D components to a 3D mesh or model that can be 3D-printed.

Another factor to consider when using 3D-printing is the method that the 3D-printer, and printer software use to produce the object. Some printers operate differently, even if they are the same type i.e., FDM, and may require the geometry to be constructed in such a way that the printer can process and build the object correctly. This often means having the knowledge to generate clean and well-constructed 3D models. Additional processing including cleaning, setup, and optimization of printer settings, and preparing the 3D-printer hardware. Depending on the type of 3D-printer, for example FDM, the digital model must be generated to support printing methods without error. This includes reducing intersecting or overlapping geometries, setting layer height, infill, and shell thickness parameters, leveling the 3D printer plate, and setting the extrusion temperature as required for the specific 3D-printer, object, and extrusion hardware type.

However, there are a variety of other techniques that can be used to generate 3D models for 3D-printing purposes. Figure 2.5 summarizes many possible inputs and data transformations all resulting in a digital 3D model that can be produced using 3D-printing (Kaplan & Pyayt, 2015). 2D images can be converted to 3D meshes using pixel data, such as color and position, to generate curves that can be lofted and extruded. Another method requires multiple 2D images or photographs to be combined in 3-dimensional space to form a volume and meshed to generate a 3D model. This is seen in photogrammetry where computer vision, and spatial computing is used to convert hundreds or thousands of photographs to a 3D model. 2.5D or multidimensional imaging can also be used to build a 3D volume, that is then converted to a 3D mesh. Many medical imaging technologies such as magnetic resonance imaging (MRI) and computed tomography (CT) can be used to generate 3D models with this method. Alternatively, 3D surface scanners can be used to capture and convert actual physical and spatial information into 3D point clouds that can be used to generate 3D meshes and models. Using Computer aided design (CAD) software provides another technique that can be used to build 3D models that can be reproduced using a 3D printer. Using CAD software, the developer builds 3D geometry using basic 3D volumes, and curves to generate 3D models. Other techniques for generating 3D mesh that can be 3D-printed include mathematically modeling and graphics program that can be interrupted by the 3D-printing software to generate the physical object generally without viewing a digital representation prior to printing.

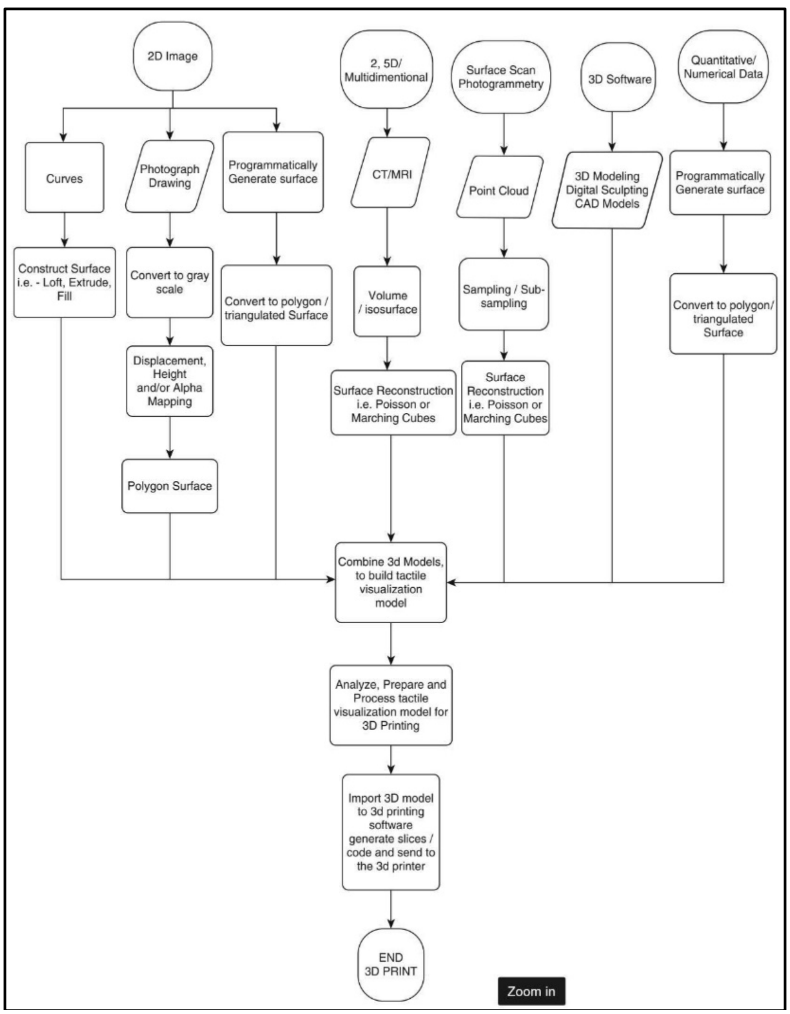


Figure 2.5 Schematic of different approaches to 3D-printing of tactile visualizations based on input data. Used with permission from Springer Nature.

Chapter 3: The Design and Development Process with Visually Impaired Users

3.1 Introduction

In this chapter we discuss the perception and strategies used by people with blindness and low vision to read and comprehend using their sense of touch. Then we describe the iterative development, production, and testing methods used for the process of creating the 3d-printed tactile maps. We then demonstrate the parameters and components for the design of Braille and raised text 3D-printed tactile map keys.

3.2 User Perception and Strategies

In spatial cognition research of blind and visually impaired individuals, a more general view is given with respect to haptic or near space versus locomotor or far space. There are two general categorizes related to spatial perception of these individuals the first, small-scale, being areas that require minimal movement typically done when exploring and reading objects that can be held, such as tactile maps. The second being larger spaces that require full immersion or body movement, for reading and comprehension of spaces, such as classrooms or offices (Ungar, 2018). Both perceptual strategies are important to this research since the user of the tactile map requires small-scale manipulation and reading to translate the map to meaningful representations of larger areas.

There are various styles and methods used by people with blindness and low vision for reading and learning using tactile items. While working on this study researchers made, and recorded observations related to the strategies used to explore and read the tactile maps and map keys. For instance, through systematically exploring an object a user must gather information over time to determine relationships of an objects components that can be connected to build a mental representation of the whole object. This requires the user to both obtain an overview of the entire object while also reading, learning, and understanding each of the object's components. Typically, when reading an object, the user requires multiple passes since they are physically, via touch, and mentally processing both the object to construct the overview and component pieces simultaneously. This is especially true for unfamiliar objects and spaces. A person living with blindness or low vision must be able to orient and navigate using a sequence of cues. Each individual may determine their own cues (Voigt & Martens, 2006).

3.3 Iterative Process

Designing for individuals with impairments involves learning and building an understanding of their needs so that the product can easily be used by the individual, while also functioning properly. In general products and services designed for individuals with impairments involves a process where the user(s) provides direct feedback that the designer uses to develop the product and test multiple revisions. This iterative process is seen in areas of assistive device and technology design, such as prosthetics, and mobility aids (Mayilvaganan & Bothra, 2017). Furthermore, the unique experience of individuals with impairments allows the designer to gather more data thus being more informed about the needs of the specific user. This type of Human-Centered Design (UCD) methodology involves adopting an outward to inward approach to developing necessary functionality and features that benefit a specific target user or group. This method is similar to Design Thinking in that the process of designing a product or solution exposes the designer to the unique challenges and needs of the end-user. These methodologies of design and development are human-centric and require a hands-on approach to prototyping and testing between the designer and end-user. For the design, development and testing of the tactile maps we utilized the five-stage Design Thinking model (Figure 3.1) created by the Hasso-

Plattner Institute of Design at Stanford (d. school), (Dam & Siang, 2018). This model involves working with design experts, in this case the researchers, and the user to develop an understanding of the end-user's experience, motivation, and needs as they relate to the product or solution. Once this information is gained a problem statement can be created to help steer the design and development of the solution as it provides a solid background on which to build. In the development of tactile mobility maps the design statement follows:

Provide accessible tactile maps with novel cartographic encodings containing vital information that is displayed optimally for blind and low vision users to read and understand so that they can use the map(s) for mobility and orientation of interior locations.

The next phase of the design thinking process is to generate ideas, and possible solutions. During this ideation phase it helps to conceptualize multiple solutions to determine the best possible solution. Within this ideation phase we also explore various production methods including materials, and techniques to determine efficient, cost effective, and accessible production methods. Once, an idea has been found, a prototype is built so that it can be user-tested. In terms of the tactile maps, 3D-printing allowed prototypes to be quickly produced and tested enabling us to test several styles of maps and collect user feedback. The last stage, testing, was used to evaluate the product or solution, to build a better understanding of the user uses the product, as well as the effectiveness of the product during and after use. The testing results are used to refine the product by removing problem areas and adding or adjusting elements to enhance the item. Through this iterative user-feedback approach the decision-making organically evolves from end-user contributions. For the tactile maps, the selection of what is represented and how the representations are displayed tactually are based-on the user evaluations, feedback, observations, and iterative developments. This user-centric, Design Thinking, and iterative process eliminates any assumptions or bias from the developers and designers and allowed us to focus on solving the problem.

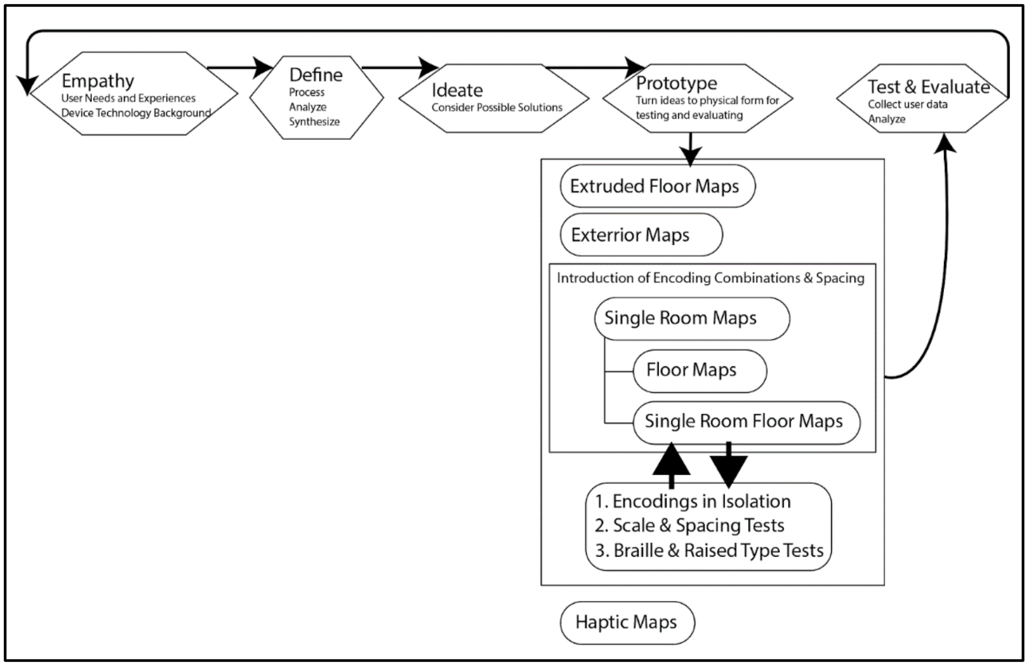


Figure 3.1 Iterative design and development process, for users testing of the tactile maps.

3.4 Braille and Signage

Braille and raised text are necessary tactile communication systems for people with blindness and low vision. Therefore, we determined that these systems be included in the maps and map key. However, the inclusion of Braille and raised text were only applied as a function of their utility. Meaning, that they were included to describe the map encodings in the map legend or key and inform the user of the mapped location. Whereas the visual and navigational elements were described using tactual symbols or encodings. In the Braille system size, spacing and texture are vital components of its functionality. In standard Braille A cell contains six dots in a two by three column. A raised dot can appear in any of the six positions, producing sixty-four (2^6) possible patterns. Measurements for standard braille define the dot spacing within a cell to be between 2.3 and 2.5 mm, the cell to cell spacing to be 6.0 to 6.2 mm, with a base diameter of the braille dots to be approximately 1.44 mm, and the dot height to be 0.25 to 0.53mm (Bogart, 2009; Braille Authority of North America, 2015). As mentioned in the previous chapter, Grade 2 Braille is the most common form used. Other forms of braille have been proposed, including micro, eight dot, and other abstracted symbols, however, none of these have been widely accepted or standardized.

It should also be noted that for a specification to become legally required, the guidelines from the US Access Board, a group responsible for developing guidelines for the implementation of the Americans with Disabilities Act (ADA), must be approved by the Department of Justice. Additionally, individual states have the right to determine their own laws on subjects not specifically mandated by the federal government if they meet the minimum standards and gain approval from the Justice Department (Braille Authority of North America, 2015). Therefore, no real "standard" for braille signage is available since each state can create their own requirements as part of building codes. However, many comply with Americans with Disabilities Act (ADA) guidelines for using braille size and spacing requirements.

3.4.1 Map Legends

Maps for sighted people are generally accompanied by a map legend or key to provide map readers with descriptions of cartographic symbology used in the map to represent specific items such as, location, and travel routes. The use of symbols provides a clearer more accurate representation of the layout of the area improving the map functionality. Like maps for sighted individuals, tactile maps require a map legend to describe the tactual encodings used in the map display.

3.4.2 User-testing of 3D-printed Map Legends

For this study multiple 3D-printed Braille legend plates were created and user-tested. Users were given the 3D-printed plates and asked to evaluate and provide feedback about the surface, size of braille, and readability. Overall legend size, orientation of elements including Braille, and layout was evaluated to determine optimal properties based on the user and map requirements. Various Braille dots were 3D modeled, printed, and tested to determine the optimal solution for the 3D-printer settings, and materials of the map legend (Figure 3.2). Additionally, map legends were provided in both braille and raised text since some individuals in this user population can only read one or the other, raised text or braille. User-testing was conducted with one participant at a time, with two researchers. Notes and photographs were taken during the study and later analyzed. The study time ranged from 20 minutes to 40 minutes.

Figure 3.2 3D-printed Braille test plates with different dot styles and parameters.

3.4.3 Findings of User-testing of 3D-printed Braille Map Legends

User-testing revealed that certain layout consideration should be made when designing and providing a map legend. For instance, all the encodings and descriptions should be listed vertically with one encoding per line. Over several iterations' findings showed that the participants preferred the legends that displayed the encoding first followed by the description. Additionally, all the encodings and descriptions were better received when they were vertically aligned, as opposed to staggered, (Figure 3.3 & Figure 3.5).

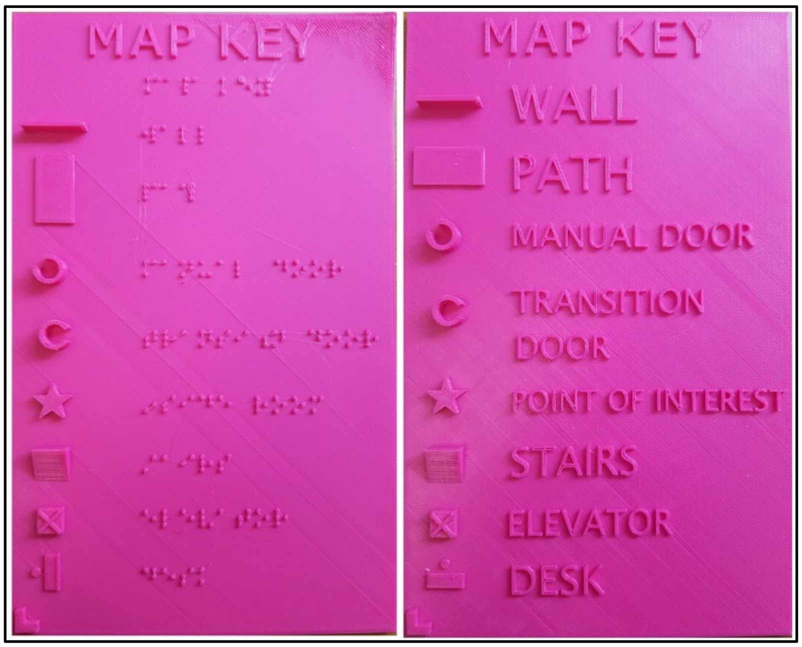


Figure 3.3 3D-printed legends with vertical layout.

We also noted that the tactile maps and legends with textured background surfaces, produced by the 3D-printers, interfered with the user's ability to read, and understand the information. This occurred in both raised text and Braille versions of the map legend. FDM printing often produces surface textures and roughness caused by the material, extrusion limitations and movement system. The rough background surface hindered Braille reading and negatively impacted the functionality of the tactile map legend. Therefore, 3D-printed tactile map legends should be produced with as smooth a surface as possible to eliminate surface noise.

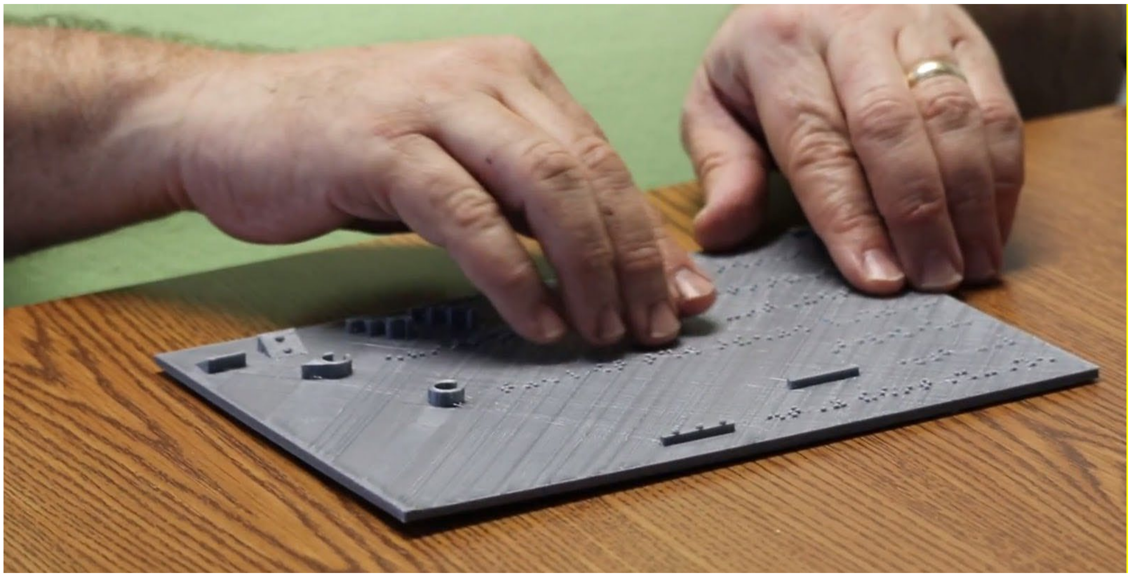


Figure 3.4 Participant using a 3D-printed Braille key with staggered encodings.

When 3D-printing Braille, standard parameters must be considered. However, there are printing limitations in terms of the size and texture of individual braille dot production. Most consumer grade 3D-printers cannot extrude the material at the required size needed to meet Braille requirements. It was concluded that 3D modeling and FDM printing of Braille to achieve optimal parameters can be done with slightly varying measurements when compared to 2D Braille (Table 3.1) (Figure 3.5). We determined that the differences in sizes were due to the limitations of FDM 3D-printing.

Table 3.1 A comparison of 2D printed and 3D-printed Braille measurements.

Object	**2D Measurement range**	**3D Optimal Measurement**
Dot Base Diameter	0.059 (1.5mm) to 0.063 (1.6mm)	1.75mm
Distance between two dots in the same cell	0.090 (2.3mm) to 0.100 (2.5mm)	2.85mm
Distance between corresponding dots in adjacent cells	0.241 (6.1mm) to 0.300 (7.6mm)	6.3mm
Dot height	0.025 (0.6mm) to 0.037 (0.9mm)	1.25mm
Distance between corresponding dots from one cell directly below	0.395 (10.0mm) to 0.400 (10.2mm)	9.3mm

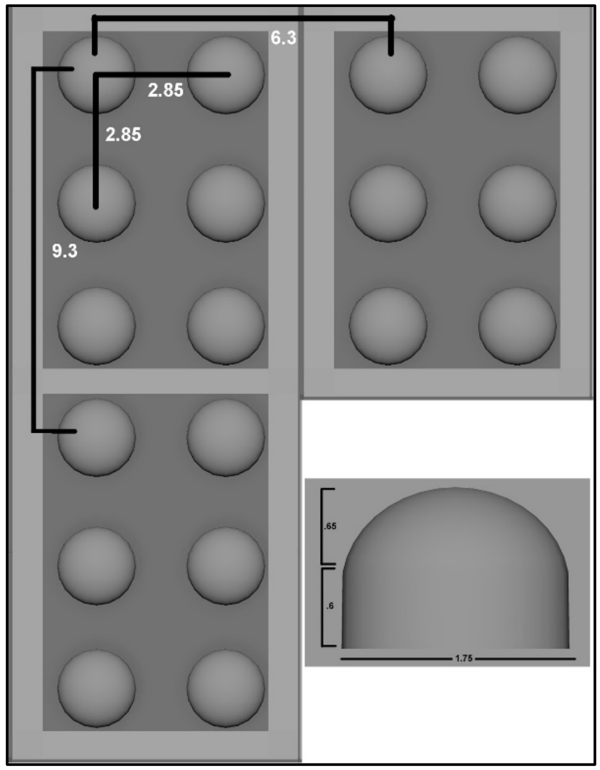


Figure 3.5 Braille cell 3D-models showing the optimal dimensions in millimeters of the spacing and size of the dots for FDM printing.

Additionally, Braille that is 3D-printed tends to have a rough or sharp texture that can be harmful and unusable (Figure 3.6). It is important to 3D-print the background without texture making it as smooth as possible. To accomplish a smooth surface, it is suggested that the 3D slicing software layer height be set to the highest resolution, (.1mm). Additionally, sandpaper, whiteout, clearcoat, or a light acetone wash for ABS material can be applied to smooth and soften the Braille if necessary.

3.5 Conclusion

Overall, user-testing revealed a need for the use of both Braille and raised text legends, the preferred sizing, spacing, and layout, and the tactual properties. These findings were in line with other studies that explored the use of 3D-printed Braille (Zhao at el., 2020). Therefore, our original assumption to include a 3D-printed map legend was confirmed.

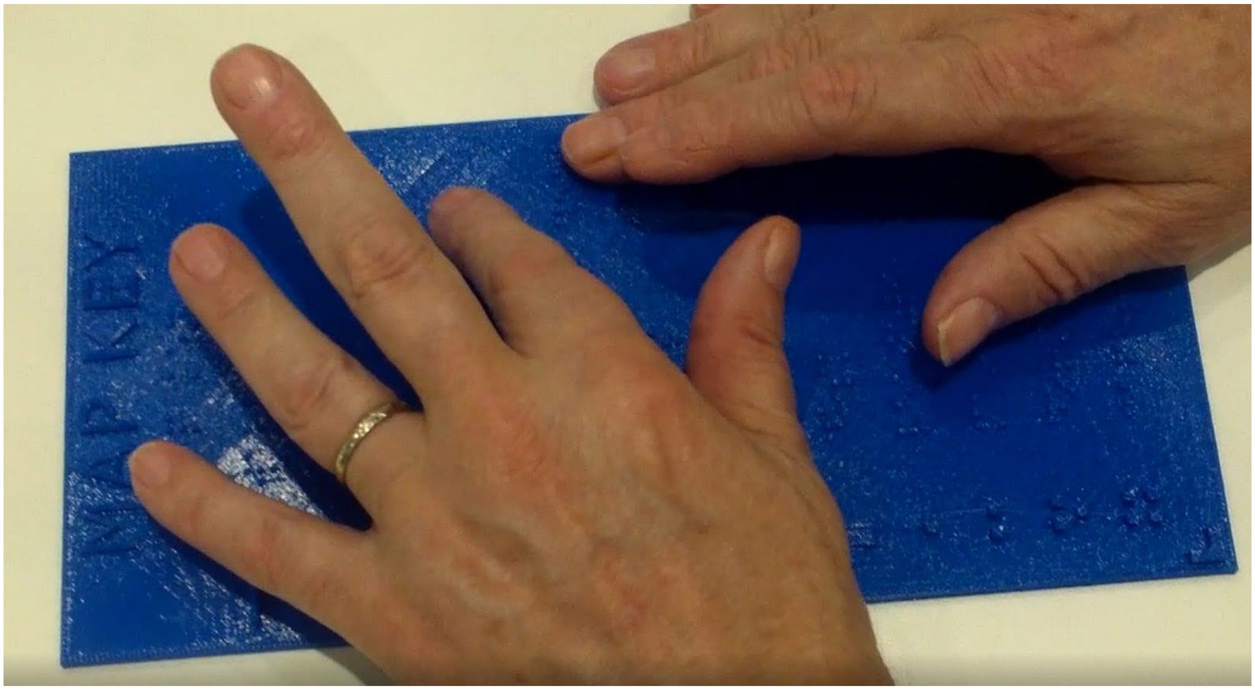


Figure 3.6 3D-printed tactile map key with a sharp braille and rough background surface.

Chapter 4: Generation 1 Maps

4.1 Introduction

In this chapter we present an iterative user-testing, and development process for interior 3D-printed tactile maps of three locations. Starting with one location, we developed and tested six tactile maps. These early generations of maps helped us to determine tactile properties that need to be incorporated and eliminated for people with blindness and low vision to better read and understand the represented location and map components. Each map was revised, and tactile components were added or eliminated based-on user feedback and observations. The first tactile maps that we developed were generated using 2D blueprint images and therefore, did not use any uniquely designed tactile encoding. We observed that this approach to tactile map making was not an effective tool for communicating spatial and navigational information to people with blindness or low vision. Following this study, we developed and tested tactile encodings incorporated in multiple map iterations intended to provide specific information about spatial elements and navigational routes. Participants were asked a series of questions about map usability, and preformed orientation and route following tasks while using each map design. We continued to build the tactile map encodings based on feedback as well as other observational data collected from user-testing. The study of six iterative maps allowed us to adjust the dimensions, encodings, and incorporate new tactile symbols, as needed. Finally, two new locations were mapped using the findings from the previous studies. Additional user-testing was conducted at each of these locations with the new maps. In the following we discuss the iterative development process, introduce basic guidelines for incorporating encodings in tactile maps, and present our findings.

4.2 Participants

An experimental study was conducted with seven congenitally blind adult participants, ranging in age from 18 to 43, in which we iteratively developed and tested tactile maps based on user feedback and observations (Table 4.1). Only one of the participants had some previous experience with tactile maps. However, that participant mentioned that the maps they used were handmade out of felt material and were not very helpful. All participants were fluent in braille and used a white cane as their daily mobility device. One of the participants had some previous knowledge of the mapped locations.

4.2.1 Testing Locations

User testing was conducted at the Conklin Center for the Blind, and at the University of South Florida (USF). The Conklin Center for the Blind in Daytona Beach, Florida, is a human services agency for multi-disabled blind and visually impaired adults and children. Over the course of three visits to the Conklin Center a total of six full building interior 3D-printed tactile floor maps were presented and tested with the same seven participants. During each visit participants tested two new versions of the maps.

4.3 Methodology

On each visit participants were seated at a conference table. Before consent was given (verbally or signed), an explanation about the testing procedures including an overview of the types of questions that would be asked was given. An IRB approved Informed Consent document was read aloud and provided to the participants. Prior to the participants receiving any of the maps a brief description of the maps and the map features was provided.

Table 4.1 Participant's gender, age, age of blindness, mobility device, braille fluency, tactile map experience, and knowledge of location.

Gender	Current Age	Age of Blindness	Mobility Device	Braille Fluent	Tactile Map Experience	Knowledge of Location
F	35	0	Cane	Yes	No	No
F	18	0	Cane	Yes	No	Yes (3 months)
M	28	0	Cane	Yes	No	No
M	32	0	Cane	Yes	No	No
F	33	0	Cane	Yes	Some	No
F	19	0	Cane	Yes	No	No
M	43	0	Cane	Yes	No	No

No map legends were developed for these initial studies. Next the study participants were given two maps to explore one at a time. Each participant could take as much time as they needed to freely explore each map. Participants were also asked to discuss their experiences out loud while using each map. After the exploration time, participants were asked to perform four tasks. The performance tasks involved using the maps to determine both orientation, and route following. Participants were asked to demonstrate the following of a specific path and to locate a specific exit on the map. They were also asked to locate the main entrance, and to orient the map to the correct facing direction. Participants could ask question and assistance was provided by facility staff or research members, if requested by the participant. Audio and video footage taken during the study session was later analyzed to better observe and review each participant's tactile exploration time and reading strategies with the maps. Once the participant completed the map tasks a five-point Likert scale was given to record and evaluate a participant's feedback about the level of difficulty they had using and obtain information from each map. A minimum of one teaching staff member from the test site and two research investigators were present at every session. Map exploration time ranged from 5 to 30 minutes, with an average study session taking approximately 1 hour.

4.4 Map Creation and Iterations

4.4.1 Initial Study: First Generation Maps

The first-generation maps were created for the Conklin Center for the Blind. Two maps were constructed based on 2D blueprints from the floor plan that were provided by the center, (Figure 4.1). We focused on creating the tactile aspects to match the blueprint and raised the walls to from the interior hallways and rooms. The first map (Figure 4.2 A.) was created on a rectangular base at approximately 20 cm x 10.2 cm x .2 cm. The second map (Figure 4.2 B.) was designed in the shape of the exterior walls of the building and printed in two pieces since it was too large to be printed on a single printer. The full map measured 41cm x 20 cm x .2 cm. We decided to generate the maps in different shapes to compare which type would be better received and understood by the participants. The first two 3D-printed tactile maps were created to be similar in style to traditional tactile maps that have been generated from 2D images where the relief was set to 1.5 millimeter. This method was also seen in other tactile maps that were generated using Google Map images (Jerman, 2016). 3D-printing the maps at this low-relief also approximates the feel of the tactual elements of similar maps produced with Swellpaper or embossers. In this study we used Adobe Photoshop, Autodesk Maya, and Meshlab to emboss 2D images into a 3D polygon surface. Pixel data from the image was used to raise the polygonal faces of the surface to generate 3D geometry in the shape of the blueprint image. Once the 3D models were created, they were exported as STL files and imported to 3D-printing software (KISSlicer, Cura, and Makerware). The settings for the layer height were chosen to be 0.1 mm, which corresponds to the height resolution of the 3D-printed model. We then oriented the models so they could be printed on the flat surface for quicker and more accurate printing with little to no support structures needed. FlashForge, and Makerbot, fourth generation printers, with linear movement, were used to print the maps with white Polylactic Acid (PLA) filament. Producing the two maps using this method allowed us to collect preliminary user-data prior to development of further interventions being introduced for the next iteration of 3D-printed tactile maps.

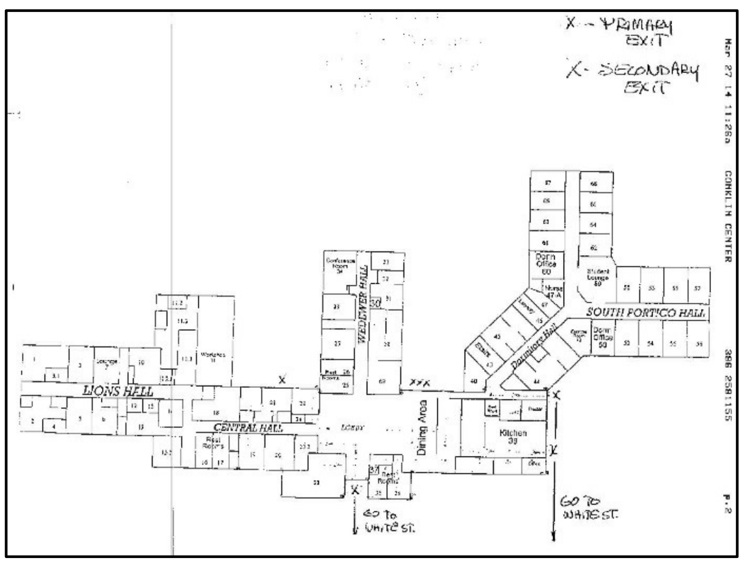


Figure 4.1 Conklin Center blueprint.

4.4.2 Study: Second and Third Generation Maps

Based on the participant feedback from the first study session it was determined that several changes and modifications needed to be made to the maps. New versions of interior maps were created, and user-tested, (map 3 and 4). The updated interior maps included new tactile encodings, such as arrows that were designed to provide information about navigational routes and hallway locations (Figure 4.3).

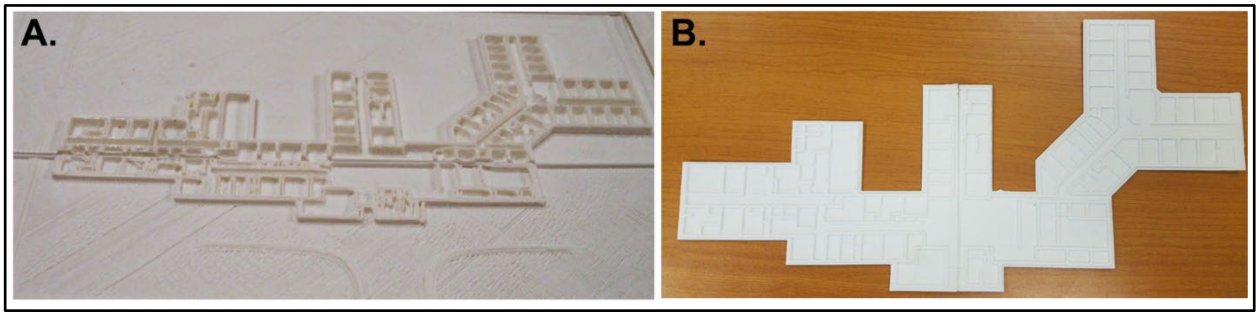


Figure 4.2 A) 3D-printed map of the Conklin Center on flat plat. B) 3D-printed map of Conklin Center in the shape of the exterior walls of the building.

Computer-aided design (CAD) software was used to 3D model the maps, as opposed to generating the maps from 2D images. This method of map generation allowed for the creation of customized geometry with specific 3-dimensional parameters. For instance, the wall height for map 3 and 4 was set to 1mm and 6 mm respectively to test for user experience with different feature heights. The arrow encoding height ranged from approximately 1mm for map 3 to 3 mm for map 4 (Figure 4.3 a and c). Map 3 was designed and printed smaller than the previous maps tested, while map 4 was significantly larger. This was done to determine if an optimal size of a tactile map could effectively provide tactile information, while also optimizing the map's readability and ease of development and production (3D-printing). The size of map 3 was 21cm x 10.5cm, and map 4 - 60cm x 20cm x .5cm. A FlashForge printer was used to print map 3 in two colors, yellow and red to determine if high contrast two color map could provide additional benefit for the users with some vision. Map 4 was printed in two pieces and developed to be larger than the other maps, because the hallway spacing was exaggerated in an effort to provide more room for finger travel within the map. Both maps were designed and printed in the shape of the building. This was done to inform the user of the proper building orientation.

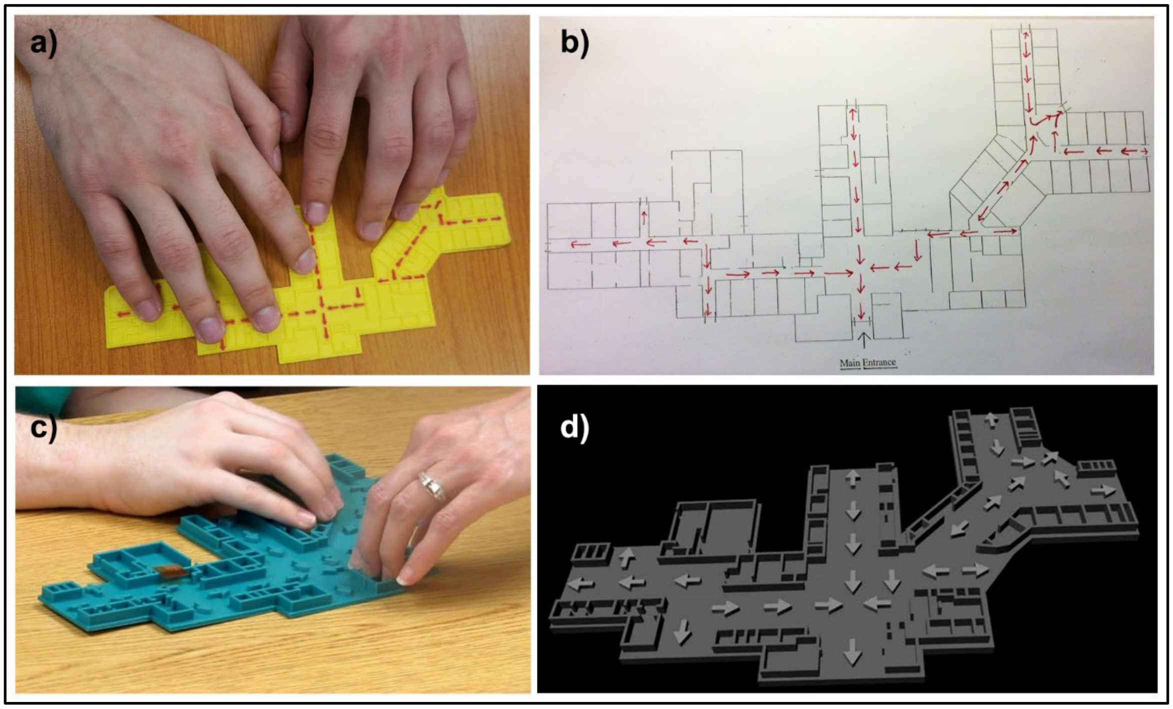


Figure 4.3 a) Participant using map 3. b) Layout drawing with new encodings. c) Participant testing map 4. d) 3D CAD model of map 4.

For the third iteration the path encoding on the map was further updated, and new encodings were added based on the user feedback. The paths were designed as connected rails with intersecting directional arrows (triangles). A ring or a diamond was placed at travel path locations to indicate that the path could go into multiple directions. A raised line was added to the map to represent the main entrance of the building. A 90 degree "L" shape was also added in the lower left corner of the maps to help the users orient the map.

These symbols were also included as a legend below the map. Each encoding on the map was set to a specific height to check if different heights might help with better recognition of different types of spatial objects represented on the map. For map 5, diamonds, arrows and paths were 4mm, and the walls were 6mm tall. For map 6, the paths were 1mm high, walls were 5mm tall, and rings, arrows and main entrance encoding had an elevation of 2.5mm. The left corner indicator for both maps was 4mm tall. The maps were printed on rectangles of 19.5cm x 28cm, on a plate height of 2mm. Both maps were printed in one piece on a Raise N1 Plus 3D printer in two colors, black and red, (Figure 4.4).

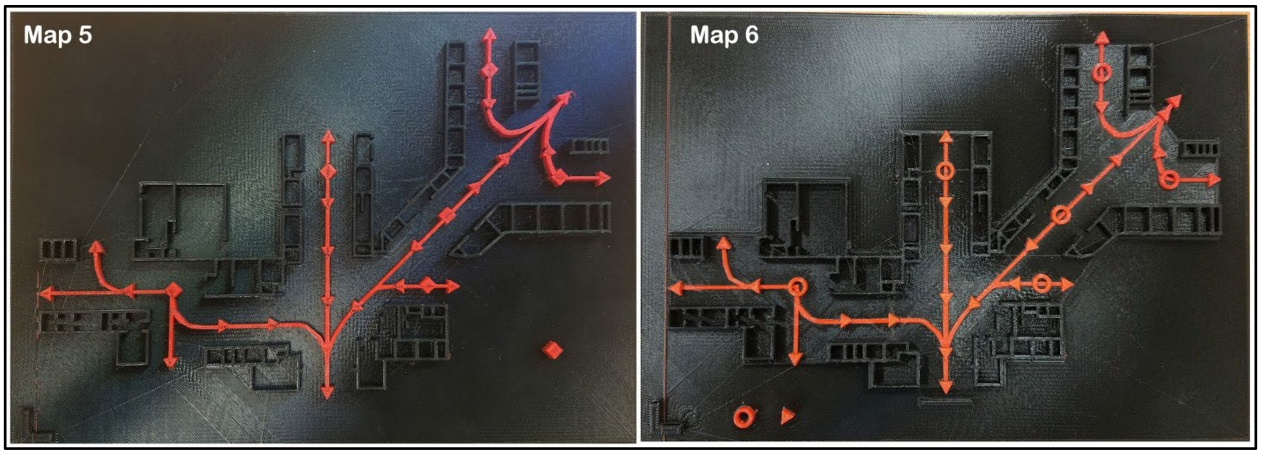


Figure 4.4 Left) Map 5 is a 3D printed map with diamond encoding. Right) Map 6 is a 3D printed map with ring encoding.

4.5 Results

4.5.1 Initial Study Results: First Generation of Maps

The critical part of the study was to collect user feedback and continuously improve the technology based on their assessment. On a positive side, all the study participants were excited about using 3D-printed maps and were interested in learning more about the technology. Some of the participants indicated that they had used tactile graphics before, but they were not as "real" or "solid" as the 3D-printed maps. This indicates that the technology had definite potential, if created properly. With the initial 3D printed relief maps, user-testing revealed that there were several problems. None of the participants successfully completed the performance tasks (Figure 4.5) that included using the maps to determine correct spatial orientation of the building, find a required route or locate the main entrance.

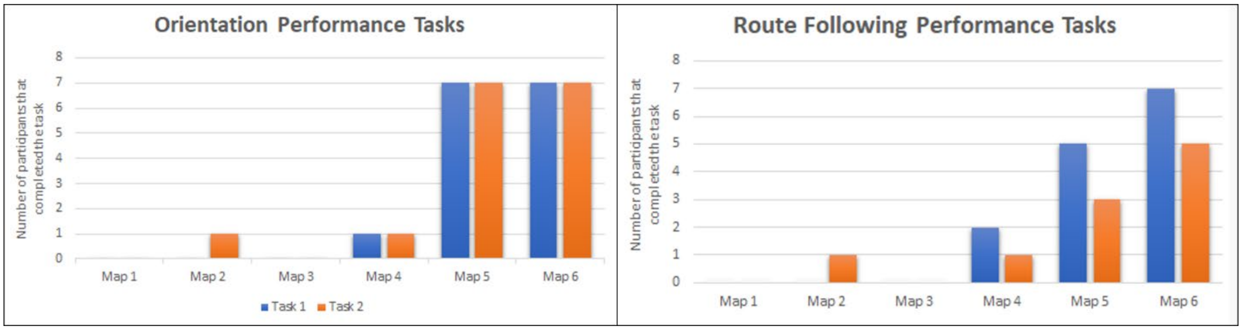


Figure 4.5 Results of the orientation and route following performance tasks for maps 1-6 by each participant.

Correct orientation of the map was very difficult for the participants and contributed to issues with general usability. The rectangular shape of map 1 did not provide enough information for participants to properly orient the map and identify the building's main entrance. This made it hard for participants to set an initial orientation point. The building shape of map 2 also caused confusion for the participants with respect to orientation and representation, since the map did not provide users with adequate spatial information to build a mental representing of the true shape of the building. This made it difficult for the participants to correlate the information in the map to the layout of the physical space. As an example, participants found it challenging to construct relationships to other spatial structures that they could use to connect with one another in order to help them determine the location of the main entrance. Navigation and location identification were also a problem because users could not identify clear differences between rooms and hallways. For example, one participant said, "I can't see the rooms."

Additional problems arose with map 2 since the it was printed in two pieces. Map reading was challenging for the participants even after help was provided. Staff members had to assist all the users with aligning the map and positioning their hands at various locations several times during map exploration and performance tasks. The spacing provided was also not sufficient for finger travel as it was observed that several of the users found it very difficult to find hallways and follow them to specific locations. One participant said, "I can't follow this, everything feels the same". Participant feedback suggested that an ideal map should be focused on structural and navigational attributes, and non-relevant information should be eliminated. These finding revealed the need to provide users with additional tactile elements that could enhance map functionality. Therefore, new generations of maps were developed to improve readability and included tactile encodings of additional spatial and structural components.

4.5.2 Study Results: Second and Third Generation of Maps

New maps and encodings were developed and user-tested, however, during testing of the second iteration of maps (3 and 4), the participants required quite a bit of verbal guidance and needed help with orienting the maps. The shape of the map did not provide an adequate method to enable the users to properly orient the maps. However, users were able to identify tactual difference between the maps, but could not consistently distinguish between different spatial elements, such as walls, hallways and arrows. Due to the limited size and spacing of map 3 it was very difficult for all the users to read using their fingers, this was due to the tactile properties of the map being too similar. Since the height of all the map encodings were the same, this also contributed to performance task, and readability issues. The lack of spacing, and low encoding height in map 3 did not provide adequate room for the display and inclusion of encodings to be discernable through touch sensing.

Participants showed significant reading improvement when using the larger map (4) since the arrows were bigger than in map 3 and hallway spacing was wider. However, only one participant was able to orient the map independently. Two participants completed the performance task for route following. It was observed that most of the participants could feel the difference in height between the arrows and walls. This tactual variation of encodings helped participants to identify travel routes more easily. It was also determined that more spacing in the hallways lead to greater continuity with respect to the user's finger travel and overall route reading tasks. The spacing also contributed to most of the participants being able to distinguish between hallways and rooms more clearly. However, identification of specific rooms was still difficult for users due to the small room sizes, clustering of walls and minimal finger spacing for rooms. Additionally, it was observed that while participants explored the map, they became confused about which direction on the route to follow. Therefore, while finger travel along the map and route identification on map 4 was improved, orientation was difficult. We concluded that this issue was caused by an inability to identify specific rooms, the size of each map, and because the arrow encoding on both maps (3 and 4) faced multiple directions. Some of the comments from participants included: “keep arrows closer together.” and “arrow tip is too thick and should be thinned out just a bit.” One suggestion was made to link all the arrows together with a thin line to create a rail that would run through the hallways. Additional feedback suggested marking doorways and providing a starting point. It was also determined that a legend or key would be useful in providing information about the symbol’s representation. A key would also allow the maps to be used more independently.

The third iteration of maps (5 and 6) showed greater improvement in performance tasks and ease of use. All the participants were able to use the left corner indicator encoding to correctly orient that maps. The main entrance on both maps was also identified by each of the participants. However, map 6 had better results than map 5 as participants were able to identify and locate the main entrance easier and on average of 2.5 seconds quicker on map 6 than on map 5. This was because map 6 utilized an encoding for the main entrance while map 5 did not. The open space at the end of the hallways on map 5 made it difficult for participants to identify the correct opening for the main entrance which resulted in increased time required for correct identification and overall map reading. The majority of the participants also agreed that the new encodings made the maps easier to use. As each new generation of maps were tested, the user "difficulty rating" assigned to the map decreased (Figure 4.6). This demonstrated that abstracted maps with varying 3D tactile properties and spacing were preferred over the image-based maps by the participants. The path encoding lead to a better understanding of the travel routes with only two participants out of seven unable to perform the path following to the main entrance on map 5. Creating the path encoding as a rail proved to be vital for map reading. Participants had trouble following the previous map paths with the disconnected arrows leading to confusion and reading errors since they could not relocate themselves with the arrow encodings in a sequential fashion often missing the encoding location. With map 5 and 6, for example, one participant commented, "This is pretty cool." Another participant said, "This is very well laid out." Although, the new encodings were better received by the participants, it was concluded that the errors in path following tasks were related to the arrows causing confusion in terms of orientation and direction. Map 6 showed better outcomes when comparing participant feedback and study observations, because the encodings were more tactually different than the other maps. One participant said, "The rings are better, they're different. The arrows are too similar.". The multi-direction rings improved location finding and reading speed as it was observed that the participants used the rings as location landmarks and finger anchors to determine spatial orientation and travel routes between locations. However, the rings were not necessarily needed to indicate multiple directions since the connected path already provided that information. Although the third iteration of maps was better received, there were still issues with respect to the information provided on the map. The maps gave participants an overview of the building's possible travel routes; however, specific room identification was still difficult for the participants. This was due to the number of rooms displayed on the maps, as well as the size and spacing of the individual rooms. Additionally, participants wanted more information about the environment, such as the types of doors and if they were exterior exits or interior room entry ways.

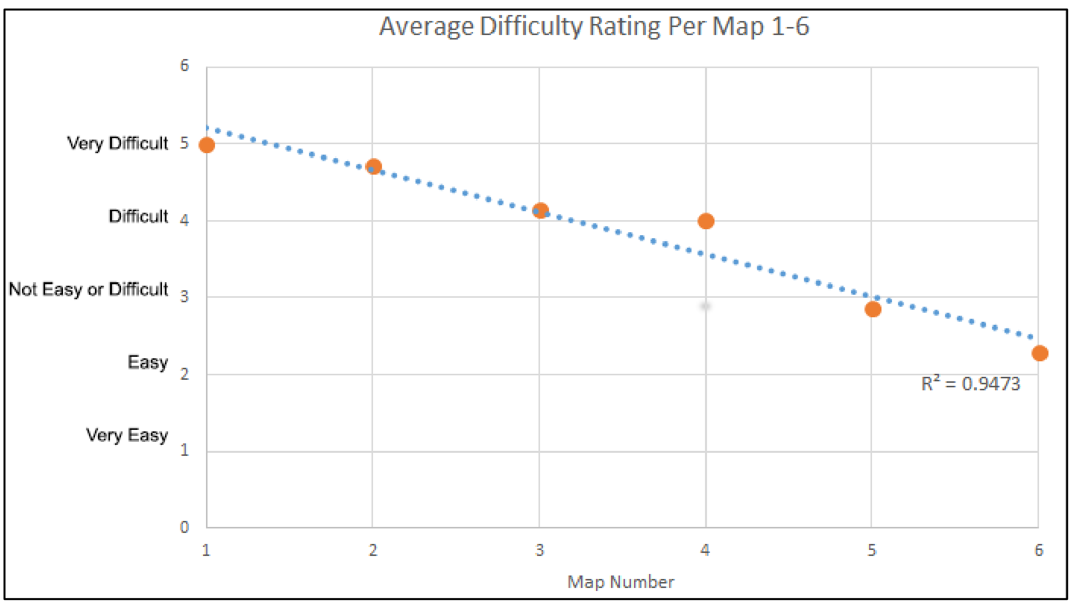


Figure 4.6 Difficulty rating results for maps 1- 6.

4.6 New Locations and Additional Study

We broadened our study to new locations and further adjusted the tactile encodings based on new locations, client requests, and user experience. However, the basic principles and encoding guidelines from the previous map studies were used to inform the development of these maps. For example, the path dimensions from the previous study were used, however, the ring encoding was omitted. We started designing the new maps adjusting previous tactile encodings and spacing, while also introducing new symbols representing additional structural elements and places of interest. For example, new encodings included: stairs, elevators, and doors. Additionally, at this stage we not only wanted to achieve excellent readability but also make the maps useful for practical applications. Therefore, in this study we not only collected user-feedback and performance task data, but also included field testing. We worked with Tampa Lighthouse for the Blind and Vispero™ to develop the tactile maps of their new office facilities. Tampa Lighthouse for the Blind provides on-site rehabilitation services for persons who are blind or visually impaired. Vispero™ is the world's leading assistive technology provider for the visually impaired and employs people with blindness and low vision. Two full floor site maps were created for Vispero's new offices, located in Clearwater, Florida. In addition to that, two floor maps were also created for a training center at the Palmetto Southeastern Guide Dogs, (a non-profit organization that provides training of guide dogs), facility. The maps developed for both sites used the same symbol set and design parameters. Separate 3D-printed legends were produced and provided along with the maps indicating the meaning of each symbol in braille and raised text (Figure 4.7). The user study with eight more participants, outlined below, demonstrates an increase usability as the maps became easier for the participants to read (Figure 4.10). As a result, the maps showed improved user's performance on the orientation and route following tasks even when used by the participants for the first time. The additional studies are described in the following sections for each corresponding facility.

4.6.1 Location 1: Vispero and Lighthouse Office Suite

Four 3D-printed tactile maps of a first floor and a fifth-floor building locations were created and user-tested for Vispero (Figure 4.8). There were two encoding versions of each map created, one with a thin path, and one with a wide path. Five participants were observed using each of the maps and provided feedback during map exploration and navigation of the space. Only one of the study participants had been to the site previously, before construction of the, before construction of the space was completed.

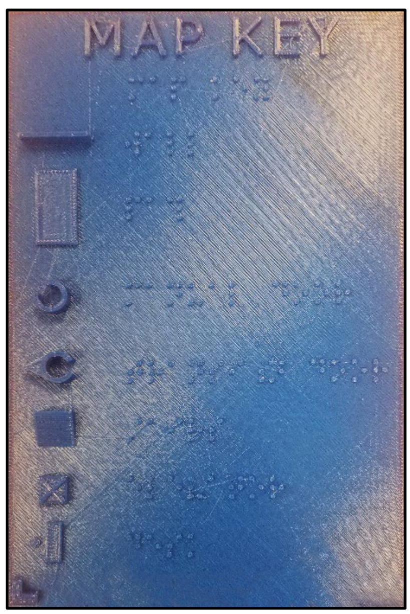


Figure 4.7 3D-printed legend showing the encodings with braille. The symbols include from top to bottom: wall, path, two types of doors, main entrance, stairs, elevator, and desk.

4.6.1.1 Performance Tasks

All the participants were able to correctly orient the maps and locate the map entrance to the building, as well as the starting point for the fifth floor, without assistance. All the participants were able to complete the route following tasks for the first-floor map. However, two of the participants required assistance with the route following tasks when using the fifth-floor maps. The first-floor map was printed at approximately 16cm wide by 22cm tall, while the fifth-floor map measures 45cm wide by 37cm tall and was printed in four pieces. Two of the participants preferred the wide path, and one found it easier to follow the route using the thin path. The other two participants had no preference. Additionally, all the participants were able to identify the doors, stairs, and elevator encodings. Only two of the participants referred to the map key more than once while using the map.

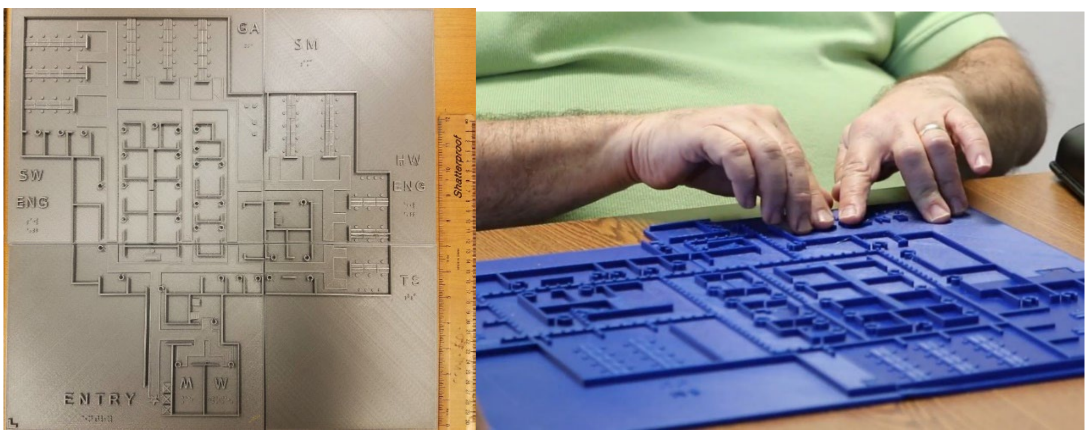


Figure 4.8 Left) Fifth-floor map currently in use at Vispero. Right) User testing an earlier version of a fifth-floor map.

4.6.1.2 Field Testing

During the field test, all participants completed the first-floor navigation without assistance from staff, successfully finding both an elevator and a cafeteria. All participants also referred to the map at some point to locate travel routes, stairwells, elevators, rooms and exits. We observed one participant refer to the map twice and two participants refer to the map three times. These participants used the map to determine the location of the elevators, cafeteria, and the direction of the office sites. One participant used the map to navigate to the cafeteria, and to check their orientation for the direction of the main reception desk. One participant had trouble navigating the fifth-floor location when compared to the other participants, because they did not take the shortest travel route to reach the destination. This participant indicated that they were more comfortable taking the route used previously, and as a result took a route that was a greater distance, resulting in more time needed to travel to the office location.

4.6.2 Location 2: Southeastern Guide Dogs

There were two variations of the tactile maps for the Southeastern Guide Dog facility, one with a wide path and one with a thin path (Figure 4.9). It should also be noted that three sizes of the maps were also printed and tested. The map sizes ranged from 29cm wide by 23 cm tall, to approximately 21.5cm wide by 17cm tall. During user-testing the larger map size was preferred. Three participants took part in the study and provided feedback while using the 3D-printed tactile floor maps. Two of participants had very limited knowledge of the location and one participant had not been to the location. Each participant was given one map at a time along with a map key. All the participants used the braille key. The participants were given as much time as they wanted to freely explore the maps and ask questions. Once the participants were finished exploring the maps, they were asked to complete the orientation and route following performance tasks using the map.

4.6.2.1 Performance Tasks

Two of the participants completed all the tasks without any issues and rated both maps as *easy* to use. The third participant, a male 66 years old, need guidance identifying specific rooms, such as the cafeteria, when using the map for the first time. However, when given the second map, he was able to navigate the path to certain rooms with less assistance. This participant rated the map difficulty as *Difficult*. Two participants had more preference with respect to the path encoding, while the third participant found it more difficult to follow the wide path encoding. This participant said, "it (the path) is not raised enough.", and when asked about the map size, would prefer a large map.

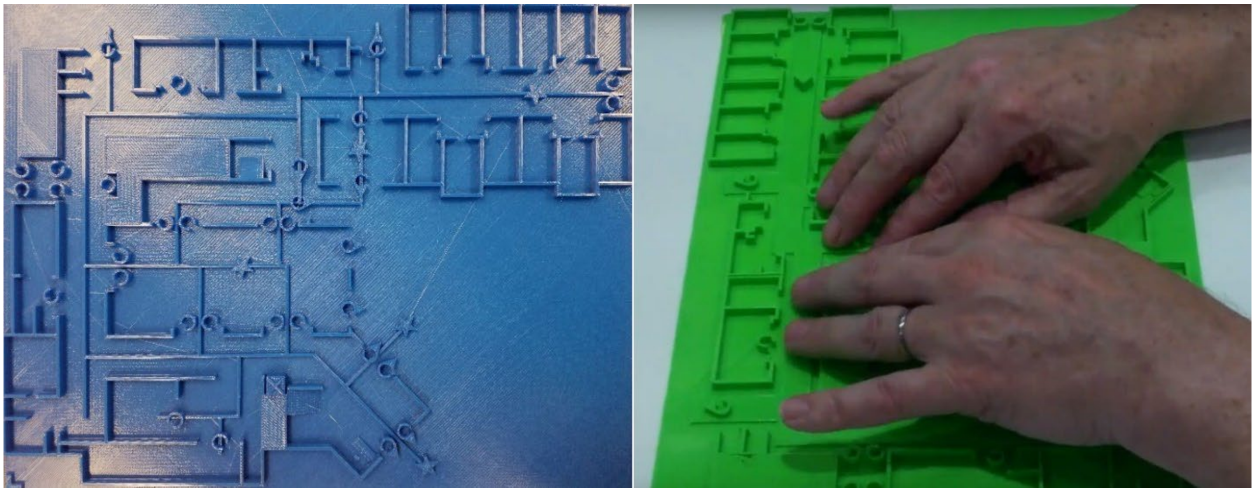


Figure 4.9 Left) Tactile map of Southeastern Guide Dogs facility. Right) User testing a version of the map.

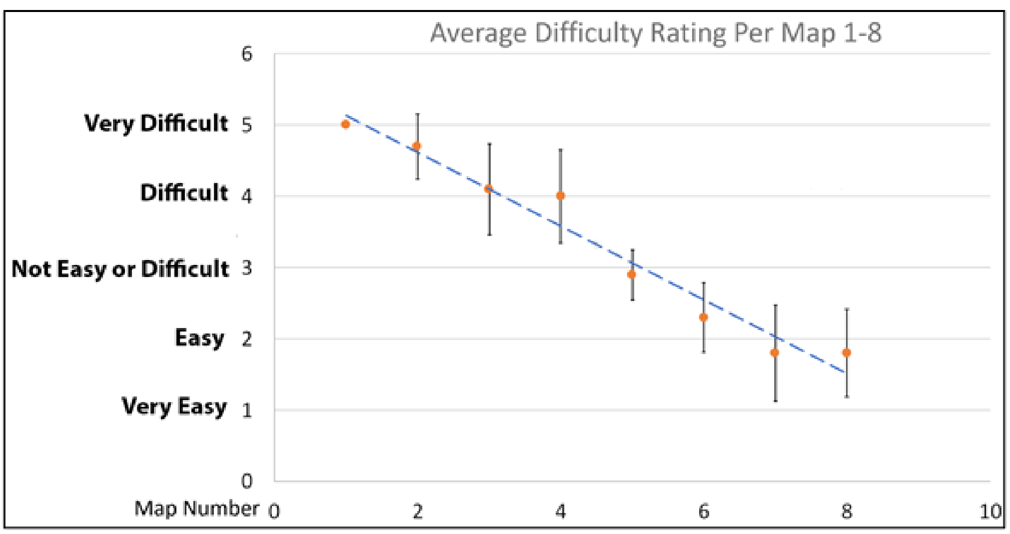


Figure 4.10 Difficulty rating results for maps 1- 8.

4.6.2.2 Field Testing

During field testing two participants were able to navigate to the locations without any issues. One of the participants referred to the map constantly and asked for assistance five times during field test exploration to confirm their current location. Another participant paused twice to use the map, once at the beginning of the test, and later to check orientation while navigating the hallway just before making a turn.

4.7 Discussion

One of important findings of this study was that direct use of imagery designed for sighted people, such as blueprints, was not an effective tool for generating tactile maps for people with blindness. Simply raising an illustration of an environment or space does not produce adequate tactile properties that can be translated to meaningful information by the user. The initial study also highlighted the need to produce a set of tactile encodings that could enable users to effectively read and understand the map. However, map encodings should be developed to be clearly distinguished from one another. In addition, since the dimensions and extrusion heights of the walls for lower-relief 3D-printed maps was challenging for the users to understand, further adjustments could be made to increase the wall heights. User-testing also showed that the current standards based on embossed and microcapsule maps that can only produce a single height can be outperformed with 3D-printed maps. Furthermore, tactile elements need to be varied with respect to size, spacing, and shape.

The iterative development and testing process revealed that maps should be produced with specific elements representing spatial and structural objects and that these elements or encodings should have varying dimensions and tactual properties, such as height, curved or rounded shapes and straight edges. Specific representation of spatial elements must be developed in order to provide users with easier and more distinguishable tactile properties. These studies show that a user must go through the process of decoding, through touch, in order to assimilate the tactile display. While the process of map reading and the strategies used can be different from one user to another, when the symbols and spacing are incorporated a certain way reading time and symbol identification can be made easier. These findings suggest that map features should not be based on actual space measurements and proportions as this can reduce spacing required for finger travel and encoding integration leading to poor readability by individuals with blindness. Instead, the actual space proportions can be represented by abstract and distorted spacing on the map enabling better finger travel, encoding integration, and overall improved tactual information delivery.

The purpose of the maps developed for these studies was to introduce and enhance the user's knowledge of the location. All the maps presented displayed a large area with many rooms and travel routes. For example, the map developed for the Conklin Center, containing over 70 rooms, including electrical, staff offices, and storage spaces. Displaying all of the rooms in a single map presented issues with respect to participants being able to identify specific room locations of interest. Furthermore, since a majority of the rooms were not used by the residents, it was determined that a map could be produced showing specific rooms of interest for a particular individual. It was suggested that individualized maps, with a similar encoding set, could provide better detail and further improve map functionality by focusing the amount of spatial information displayed on the map.

4.8 Conclusion

The studies presented, demonstrate an interest from organizations and individuals with blindness in tactile map technologies and helped us to discover unique challenges related to constructing the maps for this target population. After testing multiple generations of maps, we were able to create encodings that allowed users to easily identify spatial and structural elements of the environments and find and follow travel routes to a specific location both in the map and real locations from using the map. One very important observation was that the ability to build a mental picture of the whole building or location without a tactile map or with a poorly constructed map, was initially very challenging for a person with blindness. This was the main reason, why even after learning the shape of the building the users were unable to orient the map correctly or to find the main entrance in the initial studies. The prior information about the building could only be collected through a limited guided exposure that was mostly focused on showing simple ways to navigate to a couple of places of interest. This exposure is not providing enough information to build a mental "overview" of a complex space or large building, or even to learn about its shape. Therefore, building a mental overview of the entire building can be improved by using tactile maps since the user can fill the gaps with respect the spatial relationships using some known landmarks (position of the main entrance, restroom, or cafeteria) learning the overall layout of the building, resulting in better spatial orientation and mobility. The two sites, Vispero Clearwater office building, and Southeastern Guide Dogs training facility are currently using the maps to introduce individuals with blindness and low vision to the locations prior to and during direct experience. Future work should be geared towards further testing of the optimal dimensions and types of individual encodings for different locations, and styles of maps such as more focused single room maps. However, as new maps are developed the basic set of rules and procedures presented should be followed to make readable and useable tactile maps. And new symbols based on location, and user needs should be carefully incorporated and evaluated.

Chapter 5: Optimized Tactile Encoding System

5.1 Abstract

Wide availability of 3D-printers makes possible simple creation of tactile maps. However, while designing the map often it is done by direct translation of map made for sighted individuals. It is not focused on better readability and functionality and does not take into consideration the requirements for person with blindness to read and understand. *Methods:* In this study we are focused on development of an optimized encoding system for 3D-printed tactile maps. We use and iterative process to develop individual encoding symbols representing different physical objects and integrate them into real-world maps using continues feedback from users. Evaluation was done with the help of fifteen study participants at various locations using 3D-printed maps. *Results:* First, a set of the most important physical objects to be encoded on the map was identified based on the user requests. After that, multiple encodings were evaluated individually and while integrated on a map. This resulted in a set of optimal encodings that was most positively perceived by all participants. *Discussion:* Our study demonstrated that user feedback is critical for determining encodings that are most easily recognizable by the user even in complex maps. As a result, with each map generation we observed significant decrease in time needed for initial map exploration. The optimized maps were used for field studies where the majority of users were able to successfully navigate spaces with only using the map and their mobility device (e.g. cane or guide dog). *Implications for practitioners:* While designing and evaluating the maps an optimal set of parameters should be considered. Such as: width and height, spacing, texture, and encoding size. Also, maps can be designed slightly differently based

on their functionality. For, example, single room maps, and floor maps should use the same encoding system but might have slightly different optimal parameters of individual features and spacing (Figure 5.1).

Figure 5.1 A version of a single room floor map, with intentionally distorted parameters and spacing.

5.2 Introduction

There is a great need to develop optimal tactile encodings most “readable” by users with blindness to improve map creation, and accessibility. While previous studies were focused on optimization of individual symbol readability not included in maps, comprehension of the whole map is greatly affected by user’s ability to rapidly scan and recognize complex surface topologies. In this study we not only focus on optimization of “readability” of each individual symbol encoding different map features, but also on optimal integration of the symbols together in the map for improved user experience, faster readability, and easier spatial recognition.

Therefore, our goal is to develop the maps through continued user-testing. This iterative process of design and user-testing resulted in a new set of rules for optimal tactile map encodings.

The maps were designed with a goal to help people with blindness and visual impairment better navigate their environment (university campus, a professional office space, etc.) (Figure 5.2). We set out to develop maps that integrate multiple symbols represented with tactile encodings into readable maps, while taking into consideration optimal spacings, elevations, and relative proportions. Focused on the most efficient mini-maps centered on individual campus classrooms, office spaces, and user's direct environment with a goal of delivering information about the environment, travel paths and safety exits. Users should be able to find various locations and navigate in and out of the building. Another important use case scenario that we wanted to address is when something unexpected happens that might require immediate evacuation from the building. Therefore, the user should be able properly read and use the information about emergency exists and safe locations. It was also critical that all the development of the tactile encodings be conducted with continuous feedback from the users. All the design rules presented were developed through multiple iterations continuously improving map readability and user experience. The details of the study can be found below. The same type of objects on a map can be encoded by very different symbols. Therefore, choosing the right representation for specific information delivery was an iterative process. We tried multiple options for size, elevation, and shape while conducted user studies to evaluate which ones were the easiest for users to read and understand. Then, we created the next generation of the maps taking into consideration all prior user feedback and observations and introducing new or updated tactile features. Through multiple iterations the number of symbols that we used for the encodings ranged from 5 to 15 depending on the generation of the map. There are eight generations of maps (Figure 5.8).

Figure 5.2 Blind participant evaluating different 3D-printed tactile maps.

During the procedure, the participants were asked to feel the tactile map and provide "think out loud" feedback. A separate 3D printed legend with braille and raised text explanations of the encodings was also provided. The participants were given time to freely explore the map and use the legend. Initial map exploration ranged in time from 1 minute to 5 minutes. As participants became more comfortable using the maps, and as the encodings became more optimized the average exploration times dropped from an average of 5 minutes to just under a minute. This was even the case for user exploring maps of new locations. When the final encodings system was used for the study, the participants did not rely on the map key after one test sitting. This suggests that the encodings were easy for the participants to remember and comprehend. Even when the participants used different types of maps (e.g., floor and single room maps) they did not need to refer to the map key.

During user-testing each participant was asked to describe the strategies that they used to read the encodings and comprehend the map. Next, the researchers used a questionnaire to obtain consistent feedback from each participant about the map. The questionnaire focused on each encoding, map spacing, and the encoding combinations. Digital video was recorded and reviewed to analyze along with the other data to determine how the participants used the map.

5.3 Optimal Tactile Encodings

Below we describe an iterative process of each symbol encoding and the optimization process. This is followed by optimization of the symbol integration into a map. Finally, the preliminary results of some of the field studies are presented.

5.3.1 Paths

The most important goal of the tactile maps is to assist the user with an improved ability to safely navigate the space. While, traditionally, the floor plans and the positions of the walls would be considered the most important for a sighted individual, for a person with blind the most vital feature of a map is the pathway. Based on our early evaluations, the first request from the users was to include indicators for the pathways. The most effective encoding for the pathways required multiple designs, testing, and iterations. Our initial 3D printed map was based a floor plan and did not have any indicators for the pathways. These early maps merely had spacing resembling a hallway. This was difficult for users to understand since the spacing of the hallway could also be confused with the spacing of a room.

In the next generation of the map encoding system, we developed representation of a pathway (Figure 5.3), including: a rail, rail with arrows showing directions, and a rail with raised dots used to provide additional texture (Figure 5.3 a). All these representations were tested at various line widths and elevations. In some of the maps, pathways were interrupted by other symbols, such as doors or stairs. It was observed that if a path had a gap or was obstructed, then it becomes even more difficult for the participant to track with their fingers.

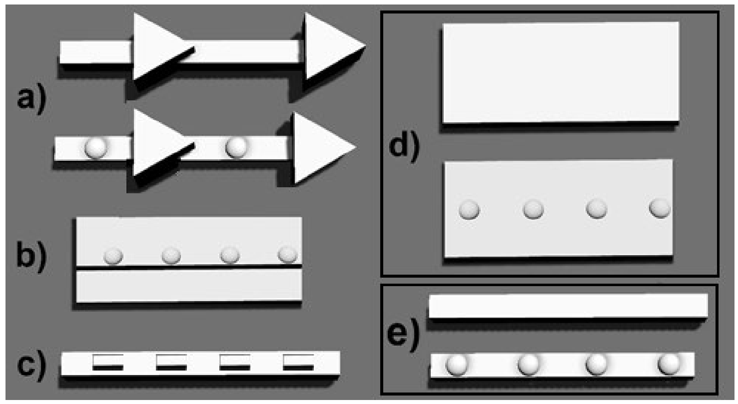


Figure 5.3 a – e) Various iterations of pathway encodings tested in isolation and in combination with various maps.

This negatively impacted the functionality of the map as disconnected paths do not adequately provide route information. The feedback from the participants revealed that a continuous path provides the best tracking results. Therefore, the optimal pathway designs should be continuous.

Another challenge was to provide the participant an opportunity to differentiate between a regular path versus an evacuation safety route path. For this reason, our solution for the tactile encoding was to use smooth rail paths to indicate regular routes and rails with dots for evacuation pathways. The use of dashed lines on top of a rail was also tested (Figure 5.3 c). Participants preferred the dots because the texture pattern translated to a sense of urgency. One participant said, "The dashed lines are a smoother texture to feel, but the dots make more sense to me, these are like harsh dots so pay attention that this is the way." This conclusion aligns well with the previous studies showing that sharp edges produce more responsive signals in the fingertip receptors than gradual slopes or curves (LaMotte & Srinivasan, 1987). Previous studies have found that rough and sharp lines are read more quickly than smooth lines. Using a pattern of dots on the path provided better and more accurate readability of the evacuation path since it was easily detected and followed by the participants. This finding relates to similar studies showing a stronger mechanoreceptor response as the finger traces dot patterns (Blake, Hsiao, & Johnson, 1997; Phillips et al., 1992, LaMotte & Srinivasan, 1987).

Jehoel, Sowden, Ungar and Sterr (2009), note that for the design of tactile maps, it is important to consider user preference. For example, although performance on the rough paths were better than smooth paths, repeated exposure to rough paths might cause the fingertips to become desensitized or even painful. Our iterative design process resulted in the non-evacuation paths to be smooth, and the evacuation paths encoded as dotted rough paths. Several of the study participants preferred this combination for navigation and readability, similarly as it was observed in (Jehoel et al., 2005).

Out of the fifteen participants twelve preferred a wider path (Figure 5.3 d), compared to fifteen preferring a narrow path (Figure 5.3 e). An interesting finding was that the older participants preferred the wider path, and the young participants liked the narrow path. The narrow path (Figure 5.3 e) was also the easiest for all the participants to follow. The wider path was difficult to incorporate in smaller maps due to the limited space, especially in areas where the path turned a different direction. When testing the path encodings with different map sizes participants performed better with narrow paths on smaller maps, and both narrow and wider paths performed well on larger maps. Therefore, it was determined that the optimal width and elevation of the path for smaller maps (10 cmx10 cm) to be between 2.5mm to 4mm. For larger maps pathways were 13mm wide and 2mm height.

5.3.2 Walls

Walls were among the first encodings to be created and tested. Users had to be able to locate and comprehend the shapes of rooms, buildings, and hallways. The comprehension of the position of the walls in space allowed the user to build a mental image of the general layout. There was a similar pattern in how participants were analyzing the walls. Most of them were first lightly touching and slowly moving over the walls with both hands. It was critical to achieve that they were able to recognize the walls and be able to differentiate them from the halls and pathways. Therefore, the encoding optimization was continued till the participants started confirming that they were able to recolonize the walls. For example, one participant was saying, “The walls are identifiable.” Another participant said: “I can clearly see the room.”

Different parameters of walls were tested and optimized. For example, the users performed better with 5mm height than with lower height of 2mm. It was also observed that the encoding for the walls should be higher than the encoding for the paths, otherwise the participants were confused. One participant commented, “"No in theory the walls should be higher than the path, otherwise there is something wrong.", and another participant said, “I prefer them because they are more realistic, than the lower 2D versions.”. Through user testing we also concluded that the optimal height difference between the path and wall encodings ranges from 1mm to 3mm. A greater difference may also work; however, it is not optimized for 3D-printing as more material and print time would be needed. Additionally, it may result in the user skipping or jumping over parts of the map with their fingertips, the tactile reading time might be increased together with the increased number of the reading errors of the map.

5.3.3 Doors

Different encoding for the doors were initially tested as isolated symbols and then as a part of the map. The 3D printed door sample plate contained four different door styles, two movable, one opening in the wall, and one circular (Figure 5.4 a-e). The door heights were between 2mm to 8mm. Optimal height was found to be 5mm. The diameter for a circular wall was between 4mm and 15mm, and the optimal diameter was determined to be 6mm. The door encodings were again integrated in the map in combination with other encodings and tested. The very first door encoding was represented as an opening in the wall. Later, one of the users suggested making a movable door that could be opened the same way as an actual door. We found out that users really wanted to know if the doors were opening inside, outside or were automatic. Even though the movable doors were liked by some of the participants as isolated individual symbols, in general, they had trouble with the doors when they were integrated on an actual map. In combination with other map encodings the doors restricted additional encoding space and limited finger movement. The functionality of the swinging was also hindered by the other encodings such as the path. Therefore, another encoding was developed and tested.

The newer door encoding design has a ring shape with a small gap to indicate a manual door and the direction that door opens. A ring with one gap indicates a manual door, while a ring with two small gaps is an automatic door. The ring symbol proved to be an easier, more effective encoding (Figure 5.4.e). The encoding provided better readability of the map for the participants since it did not restrict finger movement or caused any confusion when used in combination with other encodings (Figure 5.5). All participants were able to identify the doors in isolation and in combination tests and preferred the encoding as representing an actual physical door. However, two of the older participants had trouble reading the direction of the door opening due to the small gap size. Therefore, the gap size was increased and retested with these participants resulting in an optimal gap size of 3mm. An additional finding was that even though the older study participants had trouble with the small gap size, they preferred an overall smaller door size as opposed to the younger participants that liked the larger doors size.

Triangle shapes were added to the doors to encode the transition to and from interior to exterior spaces (Table 5.1). One participant said, “I like having the triangle to indicate the transition.” Ability to recognize the exits from the buildings helped the participants build a better mental model of the space and find several alternative routes. For example, a participant was surprised when she discovered an exit that she did not know existed. This participant said, “oh, there's a door here. Huh, that's cool, I didn’t know I could go that direction." The transition door encoding also informs the user about the location of the emergency exits.

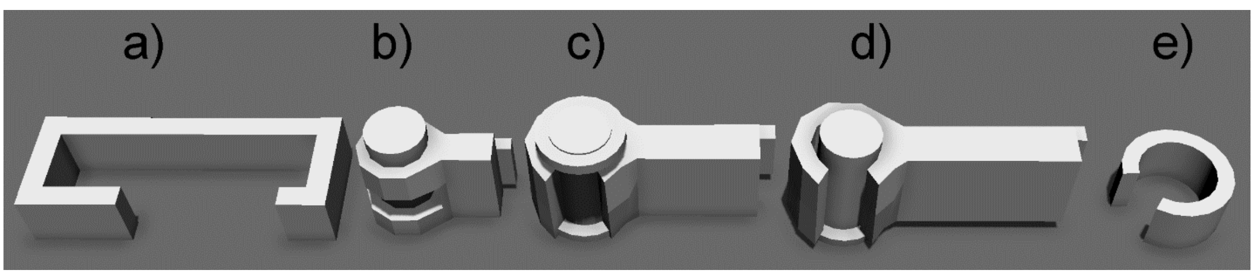


Figure 5.4 a – e) Five door encodings developed and tested in isolation and in combination with various maps.

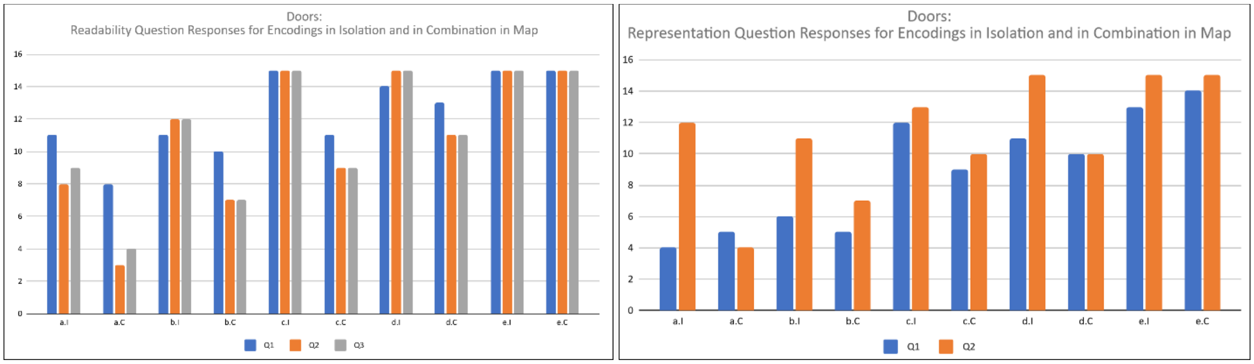


Figure 5.5 Readability and representation response results for door encodings. Tested in isolation (a.I-e.I) and in the combination on the maps (a.C-e.C).

5.3.4 Stairs

A variety of stair encodings were developed and evaluated by users. Figure 5.6 (a-e) shows five main types of stair encodings that were used individually and as a part of a map for testing with participants. Surprisingly, the stair encoding that mimicked physical appearance of the stairs (Figure 5.6 a) were difficult for the participants to recognize. When tested in isolation, participants had difficulty distinguishing individual steps which caused readability issues in determining direction. In addition to that, when the stairs were integrated into maps, some participants became confused and said that they were "to similar to the Wall and/or Path." We observed similar identification and orientation issues with two more stair encodings (Figure 5.6 b,c). These two encodings did not supply adequate 3D support as elevation was lower when compared to the other encodings (Figure 5.6: b-1mm, c-2mm). (Figure 5.6 b) was evaluated with the lowest readability and representation scores. The negative feedback from the two stair encodings was also due to the size and spacing of each step, and the overall size of the encodings causing issues in map integration. These findings were in agreement with a study conducted by D. McCallum, S. Ungar, S. Jehoel (2006) where stair symbols were tested in isolation. In combination with other encodings on the map, the three symbols (Figure 5.6. a,b & c) where challenging for the users with reading errors caused when participants felt the door symbol and other elements in the map resulted in a combined geometric shapes that were incorrectly perceived as one encoding. Stair encoding (Figure 5.6 c) was more recognizable, however, since this symbol was the same as (Figure 5.6 b), only larger, it presented problems while building the maps as space became more restricted when combined in the map. The fourth encoding (Figure 5.6 d) had better results in terms of representation and readability in isolation, however, when integrated in the map presented issues. Participants had difficulty feeling the variation of the encoding and determining its direction. When testing the stair/ramp encoding (Figure 5.6 e) all the participants where comfortable with the representation in the isolation test, and most agreed with the representation in the combined map test (Figure 5.7). None of the participants had trouble reading the encoding on both the isolation and combined tests. Based on the user feedback we believe that the texture created by 3D-printing of the ramp shape produced a ridge-like step pattern because of the gradual build-up of the additive printing process. This texture enabled the participants to distinguish the stair encoding from the rest of the encodings which were smoother. Therefore, the encoding was more easily identifiable even in combination with other encodings on a map. The participants also understood this encoding as both stairs and ramps. An interesting finding was that all the participants were not concerned necessarily with the map providing information on whether stairs or ramps were present as separate structures, rather the encoding represent a change in physical structure and elevation somewhere in the space. One participant said, "We will be able to tell if there are stairs or a ramp when we are there."

There are two important conclusions related to the choice of the encoding for the stairs and ramps. The first is that the combination of symbols, such as doors and walls, already provided architectural context notifying the user that the stairs or ramps might be present. This observation was determined based on the users' prior experience with the interior architecture. Many participants knew that they would be navigating spaces that would most likely contain stairs and ramps. The second conclusion was that visually impaired were mostly concerned about information regarding a change in elevation than specific structure used for that purpose. Therefore, including a single representation provided them with the necessary information to understand that within the space a change in elevation would occur.

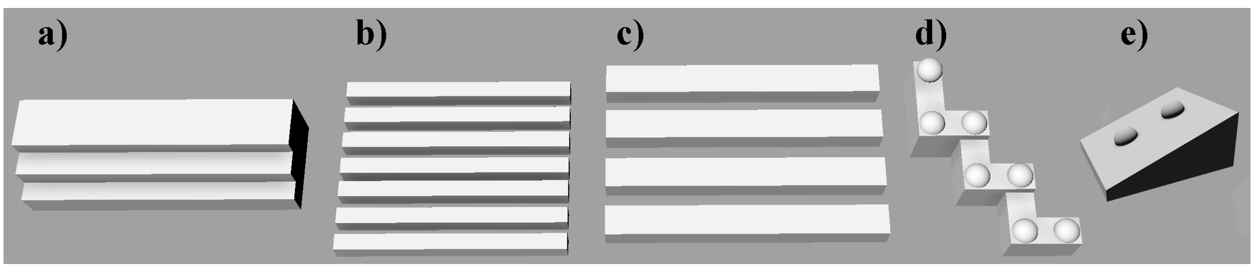


Figure 5.6 a – e) Various iterations of staircase encodings tested in isolation and in combination with various maps.

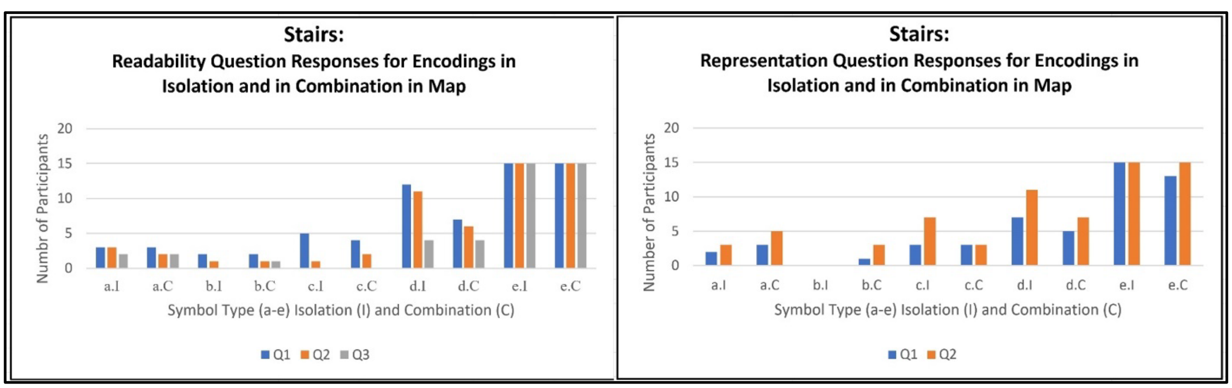


Figure 5.7 Readability and representation response results for stair encodings. Tested in both isolation (a.I-e.I) and in the combination on the maps (a.C-e.C).

5.3.5 Other Symbols

In addition to the most fundamental symbols, such as walls, stair and exits, the map for visually impaired could benefit from additional information. Because of that there are several other symbols that we studied. For example, for sighted people a star typically indicates a "You are here", position. In this study we used stars to indicate desirable locations. For example, inside of a room, or outside of a main entrance. As mentioned previously, most participants started with both hands scanning the entire map. After building a mental layout of the whole map many of the participants were then focusing down to a certain area, such as the room, and began moving along a path. Therefore, the star encoding was used to signify that the user was in the room, and therefore at the start of the potential path(s). The path of the map was physically connected with the star allowing the user to quickly identify the paths and determine which direction to travel. Various star sizes and elevations were tested. The elevation of 2.5mm received the most positive feedback and was shown to be identified faster than elevation of 0.5mm and 1.5cm. The lowest elevation was not identified by any of the participants. Another important factor was placing the star and the room in a consistent location. This meant the room and the star should be at or near the center of the map with star located close to the center of the room. Introducing maps with the room and star in other locations became confusing for the participants leading to localization issues hindering understanding of the map layout even though paths and walls were identifiable and navigable. Although these reading errors might be solved over time with additional practice on map reading.

Another example of a useful symbol was "the end of evacuation path" or "safe area" indicator. Therefore, we created and tested various symbols to represent this indicator. It was observed that curved shapes were more distinguishable when combined with the other map encodings. Therefore, a raised "S" was used in the generation 6 maps and was determined to be the optimal encoding for participants to identify the safe area (Figure 5.8 f). This encoding works in any direction (upside down, sideways), and provided the user with information pertaining to the end of the path, as well as the location of a safe evacuation locations or meeting places in case of an emergency evacuation. Through initial scanning of the map, participants were able to identify the room (star), doors and the end of the path or safe area in less than 20 seconds after having used the map once. By building a cognitive overview of these encoding positions they were then able to travel the map more effectively, since they knew where and how many safe areas there were on the map. They were also able to use other encodings, such as door rings and stairs in a similar fashion.

However, not all the experimental encodings were chosen for the optimal versions of the maps. For example, one encoding was tested and used on several iterations of the map, but was later discarded, was a raised ring indicating a path split into multiple directions (Figure 5.8 b - g). The use of multi-direction indicators allowed participants to build a general overview of the map. The idea of these ring encodings was to enable the participants to identify multiple paths and choose the direction in which they wanted to proceed. This made some participants more successful in discovering unfamiliar pathways on the map. However, once we connected the paths, and eliminated other encodings that caused readability issues the rings were not needed for multi-path indication. Therefore, since the rings were easily recognizable symbol, we repurposed them for encoding the doors (Figure 5.8 h).

5.3.6 Map Spacing and Size

Another important parameter of the map was its size and the spacing between different elements. Spatial acuity of the fingertip and finger size provided some information to the map designers about the minimum size of the tactile symbols and the spacing between symbols, when used in combination. In addition to that, the efficient use of space was an important factor for map optimization. When used alone, many types of 2D and 3D shapes are identifiable.

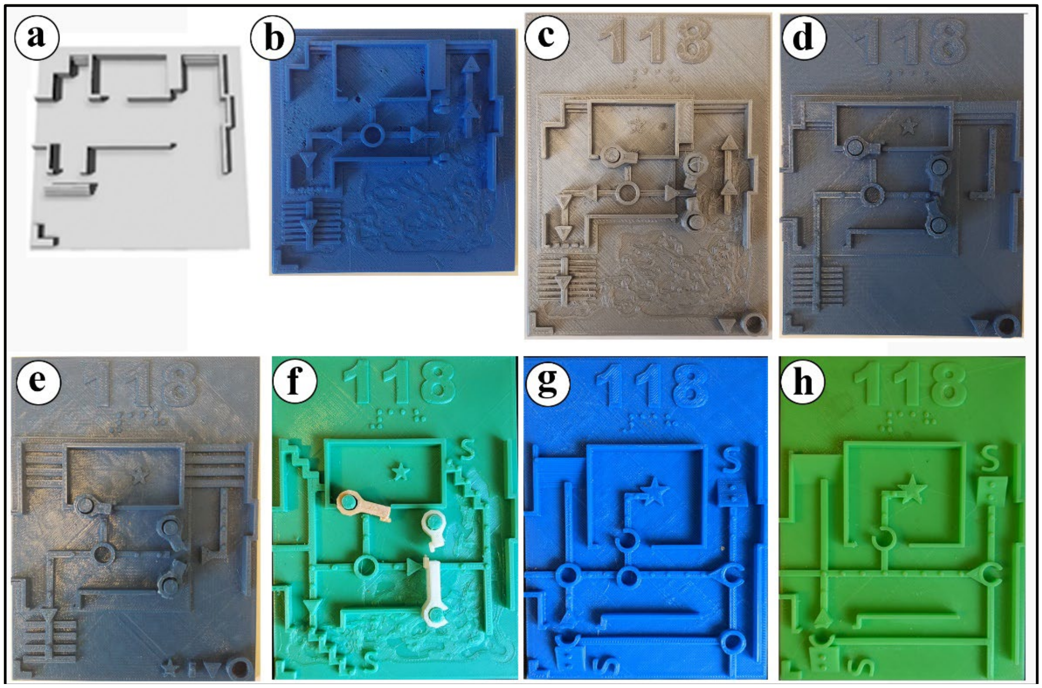


Figure 5.8 Eight generations of single room maps with iterations of encoding system over the course of testing and development.

However, when combined, many 2D and 3D shapes are misinterpreted. These errors are largely based on the space restrictions imposed when multiple shapes are used, because in combination they might be perceived as a new shape. Therefore, for the proper map creation, one must consider element spacing and finger travel, as well as the space required for users to separate different encodings. This means that, when used in combination, standardization of encodings required not only size and elevation parameters, but also the inclusion of a specific spacing considerations. For example, distance between two walls should be at least two centimeters, at least for the halls. This requirement was satisfied for the maps at least 10x10 cm in size designed for a single room. Smaller maps did not work well.

Additional map sizes were created and tested, up to 45cm x 45cm in size. However, the larger maps were found to be confusing for some of the users, as they became lost with respect to travel direction and determining their current orientation. One participant said: "The walls are here, and the path is here, but mentally I perceive this as a space that has to be crossed", (pointing at the space between the wall and path). Another participant suggesting to, “reduce the white space”. Based on the evaluations, it is recommended that an optimal spacing between the path and wall should be between 4mm and 1cm. These measurements were similar to other research conducted on tactile maps (Strothotte, 19998). Additionally, an optimal room size of 4cm x 4cm should be used on a 10x10 map (Figure 5.9). Another important consideration is that most of the encodings on the map should be connected. For example, the paths, doors, and stairs are all connected so that the user can travel along the path and sense through touch an encoding change while still maintaining their location and orientation. The only encoding that is disconnected is the wall. This design separates the navigational information from the structural information, resulting in better communication of travel routes and room locations. However, when necessary, some additional free spaces maybe be introduced for better identification. For example, in locations with open layouts such as entry ways or exterior landscapes, more space between the path and walls could provide users with more accurate or realistic spatial representation.

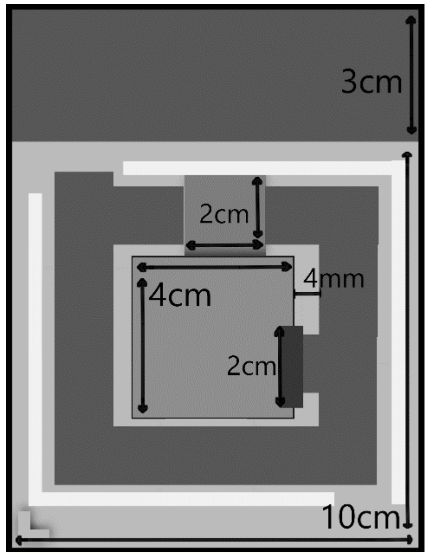


Figure 5.9 Single room map with optimal spacing measurements.

5.4 Methods

5.4.1 IRB Statement

The study was conducted by researchers at the University of South Florida under the Institutional Review Board / Human Research Protection Program. IRB approval #00033464. Informed consent was received from each participant in the study.

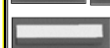
5.4.2 Study Participants

Fifteen participants with blindness took part in the study (Table 5.2) and were asked to provide feedback about multiple tactile symbols in both isolation testing and in combination with other symbols in a tactile map. The participants were also observed using the tactile maps to evaluate symbol properties, identify encodings and travel routes. The feedback and user-data were used to develop new features and encoding to improve map functionality. The average age of the participants was 34.06. The participants were interviewed and provided detailed feedback. Video and audio recordings were taken and later analyzed. Four participants from the University of South Florida (USF), Tampa campus, also took part in a field test in which they were observed using the maps to navigate to specific locations.

The data was collected and analyzed to determine optimal types of encodings and encoding rules for simplified readability of the tactile maps and proper delivery of navigational information including orientation and direction of travel. The findings from these tests also improved map design and production. The optimal encodings and spacing results provided design guidelines while at the same time decreased 3D-printing time, as the optimal map size was smaller than expected.

Table 5.1 The set of optimized tactile map encodings for single room maps.

Measurements for the Main Set of Single Room Map Optimized Encodings

Encoding	Representation	Elevation	Width	Length	Other Mesurements
	Inside Room /Point of Interest	2.5mm	10mm - 13mm	10mm - 13mm	
	Door (Manual)	5mm	6mm to 10mm Diameter	ring wall 2mm	1 gap 3mm
	Door (Automatic) with (Pyrimid, transition from interior to exterior)	5mm	6mm to 10mm Diameter	ring wall 2mm	2 gaps 3mm at approx. 5mm
	Transition from interior to exterior. **to be used with Door a enocoding*	4.5mm to 4.7mm	7mm at base	5mm	
	Stairs and/or Ramp *(with hemispheres is evacuation route)*	5mm slope to 0 mm	10mm - 20mm	10mm - 12mm	
	Path (Navigation / Travel Route)	2.5mm to 4mm	2.5mm to 4mm	x	
	Wall	5mm	1.6mm to 2mm	x	
	Safe Area	2mm to 2.5mm	7mm - 10mm	10mm	
	Left Corner Indicator / Bottom left corner of the map	2mm - 2.5mm	7mm	7mm	
	Evacuation Route Dots **must be on path encoding* **not Braille*	1.2mm	Base Diameter - 1.75mm	x	5mm spacing between
Map Base		2mm - 3mm	100mm	130mm	

5.4.3 Map Development

Map development was an iterative process; started with meeting the staff services department and the participants to determine locations and objects to be mapped. After that, initial 2D drawings for the encodings and maps were design and later 3D modelled using the Autodesk Maya. This application allowed for precise generation of 3D shapes and positioning them in 3D space. Once the 3D map models were created, they were exported as either an OBJ or STL file and imported into the Cura application for setup of the 3D-printing parameters.

The 3D-printing was done at the USF Advanced Visualization Center (AVC, 2018) using Makerbot, FlashForge, and Raise3D printers. Once the 3D-printed maps were complete, another meeting with participants was scheduled for evaluation. User observations, and suggestions were collected, reviewed, and used to improve the tactile encodings, the integration of multiple elements into a map, and to determine the kinds of maps to build (single room, floors maps, or large room maps). In addition to that map encodings could deliver different types of information. For example, safety exit routes for the building, or the layout of furniture within a space. Alternatively, maps can be focused on points of interest in the building (cafeteria, classroom, restroom, or office). Finally, some maps could combine the routing directions and the points of interest.

3D-printing allowed for the raid production of maps taking 2 – 8 hours to print depending of the size and the print resolution. Thus, a new user test could be conducted promptly, and a new map based on the user feedback could be produced after that, allowing for an iterative design and development process. This resulted in the creation of highly optimized encodings that can be integrated on 3D-printed maps designed for interior spaces (rooms and floors). The new maps allowed participants to efficiently obtain spatial information and build mental mini-maps that they could use to better understand and navigation their environment (Schinazi at el., 2015).

The connected paths allowed participants to mentally construct localized maps that are focused on specific locations of interest to them.

Table 5.2 Gender, current age, age of blindness, mobility device, braille fluent, tactile map experience, and knowledge of locations.

ID	Gender	Current Age	Age of Blind.	Mobility Aid	Braille Fluent	Tactile Map Experience	Knowledge of Location	Field Test
1	F	19	0	Cane	Yes	No	No	Yes (USF)
2	F	18	0	Cane	Yes	No	Limited	
3	M	19	0	Cane	Yes	No	No	Yes (Conklin)
4	F	30	0	Cane	Yes	No	No	Yes (Lighthouse)
5	M	54	0	Cane	Yes	Yes	No	
6	M	59	0	Cane	Yes	Some	No	Yes (Lighthouse)
7	M	43	0	Cane	Yes	No	No	Yes (Lighthouse)
8	F	18	0	Cane	Yes	No	No	
9	F	35	0	Cane	Yes	No	No	Yes (Conklin)
10	F	33	0	Cane	Yes	No	No	Yes (Lighthouse)
11	F	20	0	Guide Dog	Yes	No	No	Yes (USF)
12	M	22	0	Guide Dog	Yes	No	No	Yes (Southeastern)
13	F	38	0	Guide Dog	Yes	Some	No	
14	F	37	0	Guide Dog	Yes	No	Limited	
15	M	54	0	Guide Dog	Yes	No	No	

5.4.4 Interviews

To collect feedback regarding maps we created a questionnaire that was given to each participant. Multiple generations of maps and map symbols were evaluated, and as a result there were 3-4 meetings with each subject. Once little to no intervention was needed in proper map comprehension, the most optimal map was used for field testing. Audio recordings were taken during while participants studied the map and talked out loud about their experience. After that a structured interview, with a predefined set of questions focusing on readability, and their preferred representation of the encodings was conducted. Representation and readability were studied with the encodings in both isolation and integrated into the map. For readability, participants were asked if they could discern the encoding and determine the encodings orientation and direction. Preferred representation was determined if the participant agreed with the use of the encoding as representing a specific object. Preferred representation was also evaluated by providing maps with the same encoding more than once and testing to see if the participants were able to correctly identify the object repeatedly. Additionally, participants were given the encodings in multiple sizes.

5.4.5 Videos

Videos of the hands interacting with the maps were taken during the map testing and evaluation. Later, the videos were reviewed and detailed feedback with the specific commentaries from the users was extracted. Videos of the field tests were also recorded, and data relating to navigation with the use of the map and without map was collected. Video data also noted if the participant requested the map while navigating. In addition, videos were used for comparing the way in which study participants tactually explored the map. Most participants scanned the maps in the same manner. First, they did an overview of the entire map, often with two hands and multiple fingertips. This allowed them to analyze the whole environment and locate points of interest. Then, they used one or two fingers to follow the path with one hand and the other had to identify markers on the map. The markers chosen by the participants differed, however, the most utilized markers were the door encodings. This strategy allowed participants to track spatial orientation while also identifying locations and travel routes using the encodings.

5.4.6 Field Tests

As mentioned previously, four field tests were conducted, in which participants were given 3D-printed tactile maps prior to and during the navigation. Single room maps were used at the USF location. During field testing at least one researcher, and one local staff member was present. Participants could ask for assistance at any time. In addition to the 3D-printed tactile map, participants used their mobility devices.

5.4.7 Location: USF Field Test

Single room maps were used by four participants to locate and identify a room entrance, multiple travel routes, and exits for two different room locations. One of the rooms was previously visited at least once by each participant, while the second was completely unfamiliar to them. All of the participants navigated the locations without error. One of the participants used the map by tracking their finger along the path encoding, while walking to the exit. A second participant read the map before navigation and then was able to travel without using it again.

5.5 Materials and Printing Area of the Maps

The tactile maps used for the study varied in size from 45cm x 45cm for the full fifth floor office space to approximately 10cm x 10cm for detailed representation of individual rooms. Small area at the top of the map (10cm x 3cm) was accommodating text and braille correspond with the standard room placards used at each facility. Each map was 3D-printed in Polylactide (PLA) or Acrylonitrile butadiene styrene (ABS) standard Fused Deposition Modeling (FDM) 3D-printing filament. The maps were 3D-printed in multiple colors. An earlier test was conducted with both one-color and two-color printing and prints with paint applied for low vision users. However, the participants were not able to discern the symbols with their sight alone. Multiple versions of each map with varying encodings, and encoding parameters were modelled, 3D-printed, and tested with each user at their respective sites. Six classroom sites were mapped at the University of South Florida (USF), Tampa. Separate 3D-printed legends were provided along with the maps indicating the meaning of each symbol in braille and raised text. If requested by the participant, additional information was given verbally. Additionally, five 3D-printed encoding and scale sheets were tested by the participants. These maps and supplemental tests were created over a three-year period using an iterative design and development process discussed previously.

5.5.1 Parameters of the Individual Symbols of the Encodings

Elevation will be used to refer to height or raised encodings and spatial areas. Although, there are limitations to previous tactile maps where features on Swellpaper are generally raised by approximately 0.5 mm, and Braille embossers that produce dots at elevations of 0.25 to 1.0 mm (Gardiner & Perkins, 2002). One set of guidelines (Tactimages & Training, 2000) states a minimum of 0.4 mm should be used for elevation. However, the majority of tactile map design guidelines (Edman, 1992; Gardiner & Perkins, 2002) simply suggest that features should be of a sufficient elevation, without providing an optimal elevation that is consistent and geared towards specific map types or in combination with other map encodings.

5.5.2 Design Rules and Development

There have been previous attempts to standardize tactile map encodings using relief, embossing, and 2.5D techniques. Some of the studies have discussed the readability of various substrates and the use of different types of tactile symbols (Lobben & Lawrence, 2011; Papadopoulos & Karanikolas, 2009; Rowell & Ungar, 2003). There has been some research comparing multiple map production techniques based on user feedback. These studies have shown that 3D volumes, such as 3D-printed, graphics resulted in faster response times, (Yang, 2012). In a study by Jehoel, Ungar, McCallum, and Rowell (2005), participants preferred and had a high rate of efficacy when scanning tactile maps that used rougher substrates. Other research has suggested that tactile encodings should be abstracted from their actual physical object but at the same time contain details that allow users to connect the encoding with physical references in the space, (Celani & Milan, 2007). Further studies also discussed how tactile perception in raised-line elevation affects a map's readability. Specifically, in a study by Jehoel, Sowden, Ungar, and Sterr (2009), the design guideline for acceptable line elevation was determined to be 0.4 mm. However, these findings were based on isolated geometric shapes, and were not designed as representations of objects or for integration in maps. Furthermore the symbols that were created and tested were much larger, 6.4 mm for triangles, 5.0 mm for squares and a diameter of 5.5 mm for circles. In 2012 a five-year study by Lobben and Lawrence, testing a set of twenty-eight tactile symbols, using microcapsule paper, representing exterior elements was found to be discriminable, and easy-to-use by study participants. Information from previous studies, as well as the book Guidelines and Standards for Tactile Graphics, 2010, by the Braille Authority of North America were instrumental in the development of this study.

5.6 Conclusion

Since environments can be quite complex, traditional maps for sighted individuals use various 2D shapes and colors to represent various features. These attributes are inaccessible to people with blindness. As such, visual information can be described both verbally and through touch. Verbal description relies on a passive input experience where the user is required to mentally process the input and construct the description of spatial elements in near real-time. The verbal description is also non-dimensional and restricts spatial information. Touch sensing is an active process in which people with blindness and low vision use their sense of touch to retrieve information and build their own mental model using the tactile interpretation of spatial elements. The ways in which the individual reads the tactile display can vary, however, the interpretation of the tactile display results in a share knowledge of the representation. This shared knowledge occurs because all of the readers are interpreting the same symbols. Tactile displays also allow three dimensional properties to be described more accurately representing the realistic object or space. The development of tactile maps requires an alternative approach to encoding of physical objects and spaces. This is the reason why evaluation of tactile encodings through an iterative user-testing process was vital for improving map functionality. The ability to comprehend maps based on touch relies on the proper delivery of information through using tactile encodings to represent spatial elements.

This research is focused on the development of an optimal encoding system for 3D-printed tactile maps based on the feedback from users with visual impairments or blindness. The encoding optimization is a complex process that required iterative development of individual symbols followed by their integration into practical maps, and detailed user evaluation. The design rules presented here can be used as a guideline for the creation of the maps with improved functionality. Specifically, it was determined that there are particular shapes that allow the user to quickly recognize such objects as doors, walls, exits, stairs, paths, etc. (Table 5.1). In addition to the shapes, the height, width, spacing and texture are all very important for better readability. For example, structures on the map should be at least 2 mm tall and the spacing between two structures should be at least 5 mm. Spacing for paths for easier finger travel should be at least 2 cm. Also, while maps can be as large as 45x45 cm, for practical purposes maps 10x10 cm are very convenient. It is also important to consider how many rooms / spaces are being described in a map. For example, a single room is much better suited for a smaller map. However, this does not mean that more rooms require larger maps. The purpose of the map should be used to help inform the size. For instance, rooms that are not important to the users could be made smaller, than a room of interest. This design allows for more finger travel space while optimizing the overall map size. For the smaller maps, an optimal room size is 4cm x 4cm. Finally, the number of objects represented on the map depends on the application. Applying too many encodings can result in cluttered maps do not provide enough spacing for users to distinguish between various symbols. Although, using too few symbols can result in limited information about space, while producing large areas of blank space that do not serve any purpose, and therefore confuse the reader. Properly designed maps gave the participants a tool that allowed them to discover pathways and new objects with little effort and increase their mobility and spatial orientation.

Chapter 6: The Influence of Multi-Location Encodings in 3D-Printed Tactile Maps on Reading and Cognitive Load of Blind Users

6.1 Introduction

Tactile maps can provide a valuable means for users that are blind or low vision by allowing them to travel through an environment with efficient and easy access. Yet, compared to the maps for users who are sighed, there is a scarce availability of tactile maps. In addition, the empirically tested considerations for tactile map design are limited. When various locations on a map need to be conveyed to the user, symbols must be displayed on the map. Hence determining an effective symbol solution that enables the user to easily read and comprehend the encodings is vital. In this paper, we designed two different types of encoding structures (unique encoding vs. additive encoding) in 3D-printed tactile maps and tested if the differences in encoding structure influence users' time to recall, number of errors made while reading the maps, perceived cognitive load, task difficulty, and learning difficulty. Six male and four female users who have been diagnosed legally blind their birth participated in this study. Each participant used the unique encoding tactile map and the additive encoding tactile map in sequence with corresponding map keys provided. After the exploration of each of the maps, each participant was asked to locate the Point of Interests (POIs) on the map with random order of the locations. Participants' map reading tasks were video recorded to examine their map experiences. At the end of the study, participants completed three survey instruments measuring cognitive load, task difficulty, and learning difficulty. Using a series of paired-samples *t*-tests, we found that participants reported significantly higher task difficulty and learning difficulty when using the unique encoding structure than the additive encoding structure. However, the differences of perceived cognitive load in three sub-categories (intrinsic, extrinsic, and germane) were found not significantly different.

Tactile maps can be an important resource for people with blindness or low vision to learn and travel various spaces and environments that they are not familiar with. Although different tactile maps can serve for different purposes (for example, topological maps displaying area surface features or mobility maps for way finding (Edman, 1992)), tactile maps need to be designed to provide spatial and navigational information to those people and allow them improved independence and freedom through the gained information (Lobben, 2015). Previous studies have shown the efficiency and easiness of learning and navigating through an unfamiliar environment when users study a tactile map before and during route navigation (Blades et al., 2000; Loben & Lawrence, 2012; Passini & Proulx, 1998). Tactile maps are typically created with raised 2.5D or 3D symbols and textures that are interpreted through the tactile sense as opposed to the visual sense. Although tactile maps were created centuries ago, symbology and production techniques have been varying and inconsistent. In addition, tactile maps have been designed with any available material, which results in very different tactile symbols and features even created in the same manner. Furthermore, the tactile maps usually difficult for users with blindness and low vision to understand because the tactile symbols are designed without empirical evidence to support the design decisions. For example, relief maps are the most common form of tactile map generally produced through graphic printing production techniques. Yet, relief maps are costly to produce, require special ordering process, and do not produce 3D features that can easily identified and learned by users. Recently advanced technologies such as 3D printing has been highlighted as a production method to easily enable 3D feature design with relatively low cost

(Cavanaugh & Eastham, 2019). The 3D printing can create tactile maps with touchable 3D symbols to support effective map learning and safe mobility of people in a building.

When providing tactile maps for blind and low vision users, it is important to consider the types and number of symbols used for representation. If the map contains too cluttered symbols with varying shapes, sizes, and textures, the users will find reading the map very difficult. Tactile displays that contain many varying shapes and structures can also be challenging for users to mentally process them thus cause unnecessary cognitive overload in reading and understanding the maps. Therefore, designing proper symbols is critical to control users' cognitive load and improve map reading activities. When the symbols of a tactile display are organized or grouped in a user-friendly way, the amount of mental effort required to understand and read the map is reduced. Properly designed symbols also improve tactile map functionality because the shape and/or volume recognition of symbols is easily perceived by blind and visually impaired users. When laid out in patterns, the map symbols can create more recognizable textural properties with touch sensing. This design feature can further reduce the amount of mental effort for the user to interpret the tactual representations and help relate them to the appropriate spatial objects. Similar to braille dot patterns or textural encoding set that is integrated in a tactile map, well-designed map symbols optimize the delivery of complex spatial and navigational information to the user.

However, there are several limitations with using braille on tactile maps. Braille requires precise size, spacing, and orientation to be read. Integrating a braille encoding such as Grade 1 numerical dots would theoretically work as an additive encoding, yet it restricts the size and space requirements of the tactile maps. Further, applying braille limits the orientation and parameters for implementation because of its' rules and uses. These restrictions can negatively impact the user's ability to self-orient the map based on their spatial interest. With 3D-printing technology, there are more possibilities to design tactile map symbols. Implementing 3D volumes and tactile patterns with various sizes and configurations can provide a cohesive set of encodings in the maps so that the users with blindness and low vision can read and understand the encoding structure more effectively than just integrating braille alone. Previous studies are limited in that the influence of tactile symbol design on the users' cognitive perception of maps is unclear.

6.2 Working Memory and Cognitive Process in Tactile Maps

The design of tactile map symbols is critical as it can directly influence users' cognitive load and perceived difficulties in performing the map reading tasks and understanding the maps. Gual et al., 2014, found that twenty blind participants recalled a greater number of positions of eight abstract symbols in a key when a mixture of 2D and 3D volumetric symbols were used rather than 2D symbols alone. The results show that all our senses are used to gather information about surroundings, but our sense of vision is the primary sensory modality for spatial cognition (Pick et al., 1969; Eimer 2004). The sense of vision enables us to access highly detailed information that cannot be obtained using the other senses (Cattaneo & Vecchi, 2011). Physical three-dimensional objects can be used to communicate information through touch and vision, (D'Angiulli et al., 1998). This implies that tactual and visual exploration are interconnected in providing similar spatial properties such as direction and orientation, (Kennedy & Jurevic, 2006). Many "visual" properties such as shape and texture can be understood, and mentally reproduced contextually in a visual manner through the sense of touch. It has also been widely shown that touch has an advantage oversight, in both sighted and non-sight individuals, where comprehension of 3D objects and spatial awareness is improved because tactile capabilities allow multiple sides of an object to be read at the same time, (Heller, 2006). For individuals to obtain and use stored information in long term memory they must first build-on and use working memory (Setti, et al., 2018). WM refers to the mental system that can temporarily stores while at the same time processes a limited amount of information. The theoretical framework behind working memory is that it relies on a limited capacity system, which maintains and stores information, and supports thought processes by mediating between perception and long-term memory thus allows the execution of various daily activities such as mental processing, and decision making or comprehension (Baddeley, 2006). Many tasks including the understand of one's surrounds requires working memory processing in order to generate mental images for better comprehension of information. This functioning of working memory can be used to form mental imagery from visual, haptic, verbal, or other means, (Kennedy, 1983), but it has been shown that in the development of working memory, visual perception is not essential (Vecchi, et al., 2004). Even people born blind can store and process mental images related to spatial information by using their remaining senses (Cattaneo,2008). Other evidence has shown that congenitally blind individuals are able to create and manipulate mental images from tactile or verbal information using short-term and long-term memory processes. Similar findings have been presented in studies where both sighted and blind individuals took the same amount of time to generated mental visualizations of three-dimensional objects and spatial features and were asked to compare and describe the orientation and direction of 3D objects, (Marmor & Zaback, 1976; Shepard & Metzler 1971). Other research has concluded that mental images of blind individuals' mimics that of sighted persons even from non-visual inputs, (Bértolo, et al. 2003).

Baddeley (2006) stated that visuo-spatial information used in working memory is separated in two subsystems visual, and spatial. This suggests that other sensory modalities such as touch can be used effectively for working memory tasks. In other words, blind individuals can perform tasks that require tactile information to be stored and translated to spatial information. Vecchi's 2004 study found that the performance of blind individuals on visuo-spatial memory tasks strongly depends on how large the demand is on working memory (Vecchi, et al., 2004). Similar studies have shown that even though, the amount of time and mental effort needed for blind individuals to build mental representations is more demanding (Afonso et al., 2010). Once a tactile representation has been properly communicated and mentally stored, mental rotation abilities used to read the object are comparable with that of sighted persons (Occelli et al., 2015). It has also been shown that mental performance tasks depend on the context of tactile object used. For example, unfamiliar objects present more challenges in the creation of mental visualization than objects that are used in everyday tasks (Heller, 1989). The studies also suggest a correlation between memorization and tactual object recognition, where familiar objects are more easily understood. Röder and Rösler (1998)' experiment of image scanning showed that sighted and blind participants required the same amount of time to memorize and associate the position of landmarks on tactile maps with audio cues, and that as the distance between landmarks increased so did the time require for scanning by the participants. Often blind individuals need to navigate to more than one location within a space. For example, in a training facility the individual might have to navigate to classrooms, cafeteria, restrooms, and labs. Therefore, it is necessary to appropriately supply the location information on tactile maps in a manner that reduces reading errors and cognitive load. Yet little research has been conducted to examine the most effect design considerations in tactile map symbols for the blind using tactile maps (Ungar et al., 1997). In this study, we created two encoding symbol structures for 3D-printed tactile maps and compared how the encoding system influences users' time to recall, number of errors made while reading the maps, perceived cognitive load, and perceived difficulties including task difficulty and learning difficulty.

6.3 Methods: Tactile Maps with Two Encoding Systems

For this research we have developed two 3D-printed tactile maps. Both maps used the encoding symbols to represent five points of interest on the map. However, each map employed different types of encoding systems. The first tactile map was designed with a unique set of tactile symbols to inform the user about different locations (Figure 6.1A.). The unique encoding set contains four volumetric 3D shapes. An extruded pentagon, cube, and dome with heights of .5mm, and star at .3mm. The width of all the volumes is 1cm. The second map implemented an additive symbol set (Figure 6.1B.). The additive encoding set is comprised of a 2mm cube that is laid out in a pattern. Each location of interest has a set of cubes laid out in a pattern ranging from a single cube representing the lecture hall, to a 2x2 array representing the cafeteria. The spacing between cubes is 2mm. The locations presented in both maps included (1) two main entrances, (2) one dormitory hallway, (3) one cafeteria, and (4) one lecture room. A total of four symbols was used in each map because the main entrance symbol was used twice. Also, four different 3D volumes were used in the unique encoding map, whereas a cube duplicated and laid out in a pattern was used in the additive encoding map to indicate each location (Figure 2).

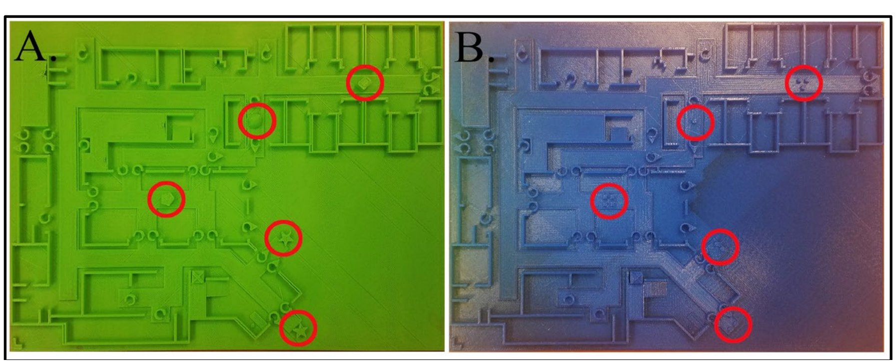


Figure 6.1 A) Tactile map with unique encodings. B) Tactile map with additive encoding.

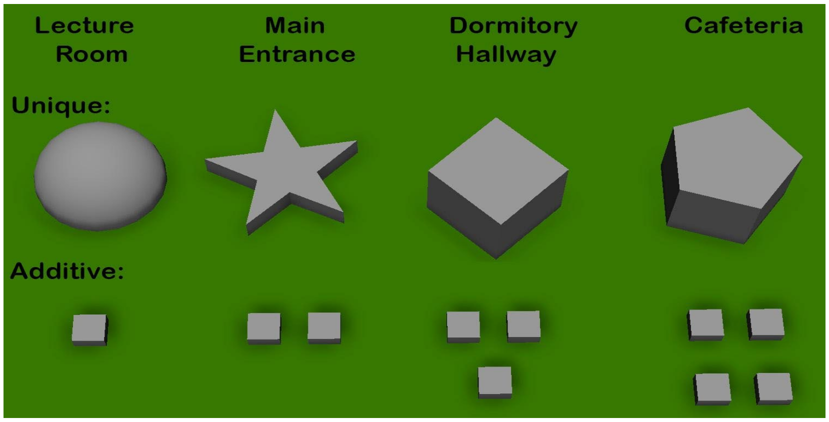


Figure 6.2 Points of interests represented on the maps using two encoding types. (Unique or Additive).

6.3.1 Participants

Ten participants took part in the study (Table 1). The average age of the participants was, 37.4. All the participants have been diagnosed legally blind their birth. Six of the participants used canes for their daily assistive device, while four participants use guide dogs. Three of the participants have utilized the space and locations that were presented on the tactile maps for one month. Only one of the participants had used a tactile map previously. However, this map was not 3D-printed.

6.3.2 Outcome Measures

We collected two types of data during the pilot test. First, we collected map reading performance data including the amount of time to recall (in seconds), the number of errors in map reading, and the number of errors in finding a certain POI. Second, we also collected participants perceived cognitive load, task difficulty, and learning difficulty while using the maps. In addition, we video recorded each participant's map reading tasks.

Table 6.1 Participant demographics

Participant number	Gender	Current Age	Age of Blindnes s	Mobility Device	Braille Fluent	Tactile Map Experience	Knowledge of Location
P1	F	18	0	Cane	Yes	No	No
P2	M	66	0	Guide Dog	Yes	No	No
P3	M	20	0	Guide Dog	No	No	1 Month
P4	F	36	0	Cane	No	Some	1 Month
P5	F	37	0	Guide Dog	Yes	No	1 Month
P6	F	22	0	Guide Dog	Yes	No	No
P7	M	43	0	Cane	Yes	No	No
P8	M	19	0	Cane	Yes	No	No
P9	M	59	0	Cane	Yes	No	No
P10	M	54	0	Cane	Yes	No	No

6.3.2.1 Cognitive Load

Cognitive load is defined as a mental effort in working memory, which contributes to "formation of mental schemas in long-term memory structures" (Sweller et al., 2019, p. 259). In this study, we measured three types of cognitive load separately using a total of 11 items: three items for intrinsic cognitive load, three items for extraneous cognitive load, and four items for germane cognitive load. All items used 11-point Likert scale adopted from previous work by Leppink (Leppink, et al., 2013), 0 meaning *not at all the case* and 10 meaning *completely the case*, with higher scores indicating higher cognitive load. Sample questions included "The topics covered in the activity were very complex" (intrinsic cognitive load), "The explanations during the activity were very unclear (extraneous cognitive load)", and "The activity really enhanced my understanding of the maps covered" (germane cognitive load). The construct validity of the instrument was reported in previous studies involving graduate and undergraduate students (Leppink et al., 2013).

6.3.2.2 Perceived Task Difficulty (IL)

Perceived task difficulty refers to the rating of difficulty in completing given tasks. We used a task difficulty item with 9-point Likert scale adopted from Ayres (2006) and Leppink et al. (2013), 1 meaning *very very easy* and 9 meaning *very very difficult*. Sample question was "Please choose the category that applies to you most: The map reading activity you just finished was."

6.3.2.3 Perceived Learning Difficulty (EL)

In addition to the task difficulty, we also measured participants' perceived learning difficulty that focuses on the maps themselves. We used a learning difficulty item with 9-point Likert scale adopted from Cierniak et al. (2009) and Leppink et al. (2013), 1 meaning *very very easy* and 9 meaning *very very difficult*. Sample question was "Please choose the category that applies to you most: To learning from this map was."

6.3.3 Study Procedure

For the work procedural settings refers to the use of the map by a blind or low vision users prior to or after directed experience of the space. Direct experience refers to a guided tour with verbal description of the space given in real-time, or by exploring the space independently. Each participant used maps with different encoding structures to determine the optimal solution. Two encoding versions were tested, unique POI and additive POI.

Each participant used the unique encoding map and the additive map in sequence. For each map testing, a corresponding map key was provided. Each participant was asked to explore each map for 3-minutes of time and allowed to ask any questions related to the map and map key (Figure 6.3). Once they had finished the initial exploration of the given map, a map key was taken away. Each participant was then asked to locate the POIs on the map one at a time. The order of the locations was given at random. The participants were not allowed to ask questions related to the encoding and the location of interest during this time. While participants completed interacting with each type of the map, we asked two prompt questions: (1) which one of the encodings were easier to feel and identify, and (2) which one of the encodings was easier to learn the point of interest? Participants' map reading tasks were video recorded for further examination of their perceptions of map experiences. After the location tasks were complete, we administered the cognitive load, perceived task difficulty, and perceived learning difficulty instruments. Questions were read aloud to the participants, as they were not able to read the written questions. All their responses were recorded for further analysis. Reviewing the recorded video clips with each participant, we transcribed each participant's think-aloud verbal reporting. The procedure was repeated for each map.

6.4 Results: Map Reading Performance

The amount of time to recall (seconds), the number of errors in map reading, and the number of errors in finding a certain POI are presented in Table 6.2.

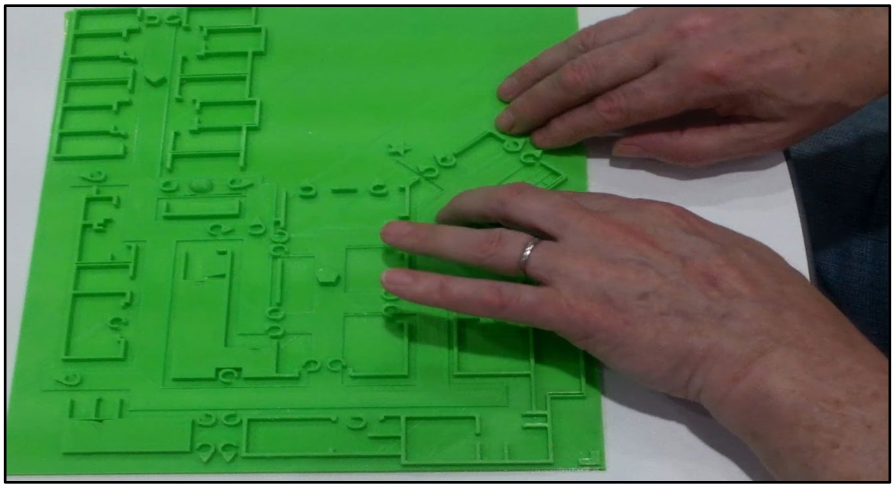


Figure 6.3 Participant using the unique multi-points of interest tactile map.

6.4.1 Perceptions of Cognitive Load, Task Difficulty, and Learning Difficulty

The descriptive data are presented in table 3. High intrinsic and extraneous cognitive loads are considered negative since they negatively affect learning outcomes, while high germane cognitive load is considered positive since it improves learning through generative cognitive processing (Mayer, 2014).

6.4.2 Intrinsic Cognitive Load

For intrinsic cognitive load, a paired-samples *t*-test was used to determine whether there was a statistically significant mean difference in intrinsic cognitive load scores between the additive map condition and the unique map condition. No outlier was detected. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = .627$). The mean difference of the intrinsic cognitive load scores between the additive map ($M = 4.57$, $SD = 1.23$) and the unique map ($M = 5.17$, $SD = 1.61$) was not statistically significant, $t(9) = 2.018$, $p = .074$.

Table 6.2 Time to recall (seconds), the number of errors in map reading, and the number of errors in finding a certain POI

Participant number	Time to recall from Main entrance to Cafeteria (*in seconds*)		Number of errors in map reading		Number of errors in finding POI	
	Unique	*Additive*	*Unique*	*Additive*	*Unique*	*Additive*
P1	12	10	3	1	1	1
P2	15	11	4	2	0	1
P3	n/a	n/a	3	1	0	1
P4	13	8	2	1	1	1
P5	9	10	3	1	1	1
P6	n/a	n/a	3	1	1	1
P7	n/a	n/a	2	0	1	1
P8	8	10	2	1	0	1
P9	18	12	2	1	1	1
P10	11	8	2	1	1	1

Table 6.3 Dependent measures and condition results.

Dependent measures	Condition			
	Unique map (n=10)		Additive map (n= 10)	
	M	*SD*	*M*	*SD*
Cognitive load [a]				
Intrinsic cognitive load	5.17	1.61	4.57	1.23
Extraneous cognitive load	3.77	1.59	3.7	0.89
Germane cognitive load	6.6	1.37	7.38	1.31
Task difficulty [b]	5.50	1.35	4.00	1.05
Learning difficulty [b]	5.20	1.69	3.10	0.88

[*] *a*= 0.05; [a] Cognitive load was measured using the Likert scale ranging 0-10; [b] Task difficulty and learning difficulty were measured using the Likert scale ranging from 1-9.

6.4.3 Extraneous Cognitive Load

For extrinsic cognitive load, a paired-samples *t*-test was used. No outlier was detected. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test (p = .938). The mean difference of the intrinsic cognitive load scores between the additive map (M = 3.70, SD = 0.89) and the unique map (M = 3.77, SD = 1.59) was not statistically significant, $t(9)$ = .186, p = .856.

6.4.4 Germane Cognitive Load

For germane cognitive load, a paired-samples *t*-test was used. One outlier was detected that were more than 1.5 box-lengths from the edge of the box in a boxplot. Inspection of the value did not reveal them to be extreme hence it was kept in the analysis. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test (p = .067). The mean difference of the intrinsic cognitive load scores between the additive map (M = 7.38, SD = 1.31) and the unique map (M = 6.6, SD = 1.37) was not statistically significant, $t(9)$ = -1.642, p = .135.

6.4.5 Task Difficulty

For Task difficulty, a paired-samples *t*-test was used to determine whether there was a statistically significant mean difference in perceived task difficulty scores between the additive map condition and the unique map condition. No outlier was detected. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test (p = .061). The mean difference of the perceived task difficulty scores between the additive map (M = 4.00, SD = 1.05) and the unique map (M = 5.50, SD = 1.35) was statistically significant with a large effect size, $t(9)$ = 3.737, p = 0.005, d = 1.24.

6.4.6 Learning Difficulty

For learning difficulty, a paired-samples *t*-test was used to determine whether there was a statistically significant mean difference in perceived learning difficulty scores between the additive map condition and the unique map condition. No outlier was detected. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test (p = .160). The mean difference of the perceived task difficulty scores between the additive map (M = 3.10, SD = 0.88) and the unique map (M = 5.20, SD = 1.69) was statistically significant with a large effect size, $t(9)$ = 4.846, p = 0.01, d = 1.55.

The study findings were also confirmed using a nonparametric statistics method, Wilcoxon Signed Ranks Test, which is equivalent to a paired samples *t*-test. We found the identical findings between the two tests.

6.5 Think-aloud Verbal Reporting of Map Experience

First participant 3 (male 20), explored the unique encoding map, followed by the additive map. While reading the additive encoding map he immediately said, "This one wins" referring to the additive map. When asked why that map wins, he replied, "I like the little squares as point of reference, for me it’s a little more simplistic then having to remember a square versus a dome." Participant 4 (female 36) was given the unique encoding map and map key. As the she explored both the map and key, we observed her hands moving back and forth from one to the other. When asked if the unique encodings were easier to read and understand, she replied, "The different shapes would be too much for me.". While reading the unique encoding map, we observed participant 7 (male 43), using both hands to jumping back and forth from the map to the map key several times. After using both maps he was asked to compare his experience using the additive and unique map, he responded, "Too many different shapes to keep a hold of on this map." referring to the unique encoding map. After using both the additive and unique encoding maps, participant 1 (female 18), was asked which map she preferred. She answered, "I think the dots (squares) for me are a little bit easier to remember."

6.6 Discussion

Cognitive resources are required to efficiently interpret, learn, and comprehend tactile maps. This pertains to the user's ability to obtain and use information provided in the map and map keys. The users working memory and cognitive functions can be observed through their ability to use various maps and the amount of mental effort needed to recognize the symbols and understand the maps. Also, tactile requirements are necessary to use a combination of symbology to create understandable maps requiring POIs. The encoding needs to work in combination with other tactile symbols for the map function. Attributes such as size, spacing, and texture are all considerations in the design process to allow for the most optimized encoding system.

Multiple POI also provided information that some of the participants used as landmarks to locate and navigate to other rooms. For example, one participant used the dorm and lecture room POI to find the laundry room which is located between the two rooms. Even though the additive encoding system uses the same symbols for maps of various spaces, working memory was used with less effort than the other encoding types. Even with repeated use of these types of maps working memory is used to obtain POI locations as representations are determined by the map creator. However, since the additive encoding system has shown positive results in all three study criteria, they should be used on tactile maps to represent different areas.

Findings of this study support the use of additive POI encodings since a high level of memory is required for people with blindness to be able to mentally reconstruct mapped environments and build relationships between locations to acquire better navigational information (Lambert & Lederman, 1989; Perkins and Gardiner, 1997). The additive POI encodings are lower in elevation and overall size than the other encodings on the map. This factor could have contributed to the results as it has been shown that a combination of 2D and 3D symbols are more easily memorized than just one type of symbol alone (Gual et al., 2014). A 1999 study concluded that a map reader can remember a maximum of seven tactile symbols on a map. (Slocum, 2005). For people with blindness or low vision haptic memory is essential for using tactile maps, (Gual et al., 2014). Including too many tactile elements on a map can influence the cognitive load of the user as they not only have to process the meaning of each symbol, but also the location and relationship to other symbols in order to construct a mental image of the environment.

Pentagon and cube were too similar; however, the star and dome were more widely accepted by the participants. This suggests that when developing tactile maps, the volumes should provide greater tactual variations when possible. If the POI is too numerous, implementing multiple height ranges could improve readability as well. Additionally, the arbitrary choices and implementation of 3D volumes to use as representation implies that users might at some point have encountered and experienced specific symbols, but the representations would most likely differ. For instance, two different map developers could utilize a 3D pentagon as a POI marker representing different locations. This could confuse, frustrate, and hinder the user's ability to use similar tactile maps (Lambert and Lederman, 1989).

6.7 Conclusion

Recommendation for maintaining optimal map function is to prioritize the additive encodings based on spacing requirements. This research looked at one site location with five points of interest. Future studies will be conducted with more participants using various map locations, and an increased number of points of interest. Using multiple floor maps at a time, such as in training session, may affect working memory. High WM, thus visuo-spatial memory load.

The Cognitive load and Mental Effort questionnaire are based off the questionnaire from Feucht and Homgren's study for Developing Tactile Maps for Students with Visual Impairments (Feucht & Homgren, 2018). The implementation of both a standard encoding set, and additive POI encodings show promise in the design of interior tactile maps. These findings indicate that the implementation of multiple POI maps using additive encodings have the potential to improve OM, and independent route finding for people with blindness and low vision. Additional studies with participants, and varying location types will need to be investigated to determine the limitation of POI encodings in terms of cognitive load, mental effort, concentration, and leaning and task difficult required by the users.

Chapter 7: Development of Tactile and Audio-Haptic Map Creator Applications

7.1 Introduction

There was a new concept that we explored while conducting our research. The idea emerged from the feedback given by participants, O&M experts, and others involved with studies described in earlier chapters. There were multiple instances were individuals expressed a need to be able to easily create tactile maps, especially like the ones we developed with optimized tactile encodings. We decided to develop a prototype application that enables users to easily create tactile maps and user test the application. We also included the option of outputting an audio-haptic map. The map creator application allows users to create both 3D-printed tactile maps, and an audio-haptic mobile maps for people with blindness and low vision. Both the tactile and audio-haptic map creator concepts are in the early stages of development and testing. In this chapter we present the development, pilot testing and preliminary user-testing results of the prototype application, and the applications output (3D tactile map model, and audio-haptic map). This work aims to provide an integrated system that is user-friendly for caregivers and mobility and orientation professionals so that they may provide maps that are more accessible for people with blindness and visual impairments. The map creator application can be accessed online by most modern browsers on mobile and desktop (iOS and Android) devices with internet access.

7.2 Current Applications

A large factor limiting the standardization and use of effective tactile graphics is the ability for non-technical individuals to easily produce and share them with the user population.

Creating tactile graphics, specifically maps, relies on not only technical skill and design knowledge, but also and understanding of the tactile properties necessary to convey vital tactile and navigational information to the user. Although there are companies that offer tactile mapping services; they are costly, contain few encodings, and take a long time to produce and receive (Lobben, 2015). Most of the map creator applications also rely heavily on GIS which produces data on exterior environments. This makes it more challenging as interior maps cannot be produced ad hoc in this manner. The Tactile Maps Automated Production (TMAP), a service that uses street locations to send an embossed map or map file that can be used independently with an automatically produce audio enabled Talking Tactile Tablet (TTT) (Touch, 2015) and (TMAP, 2019). Tactile Map Automated Creation System (TMACS) used GIS data to generate tactile maps on capsule paper (Minatani et al., 2010). Similarly, HaptoRender and TouchMapper which uses OpenStreet maps (OMS) an open-source geocoding map application, where 3D printed maps can be generated using the map image from the OMS geolocation (Kärkkäinen, 2017). However, previous research has already shown that generating tactile maps from images for sighted people, such as with Google Maps and OpenStreet maps, does not provide adequate tactile information to a blind or visually impaired user (Duann, 2014). Researchers, Lobben and Lawrence, 2012, devised a set of street symbols that were found to be discriminable, meaningful, and usable in large-scale navigational tactile maps. The symbol set contained basic geometric shapes and were designed for microcapsule paper. More recently studies of this symbol set have been applied to 3D printing and were shown to be accepted among blind users (Brittell et al., 2018). However, these types of tactile map applications focus on exterior locations, and mainly use map data for sighted individuals to build maps with some tactile elements in raised or relief. Some other digital examples of purposed solutions include systems such as LucentMaps and

TacTile which use partially raised overlays (some 3D printed) on top of a touch device (i.e. mobile phone, tablet) combined with interactive audiovisual software components. These types of device modifications and software require outside development, assembly, setup and are limited in scalability as they require continued hardware and software updates as common mobile devices and systems (iOS and Android) evolve quickly, limiting their self-life.

Since expertise, time and cost restraints contribute to limited access to tactile maps, developing a method for enabling individuals such as O&M instructors and caregivers to efficiently produce their own low-cost maps is vital to providing greater acceptance and accessibility. Studies have demonstrated the effectiveness of map reading using tactile icons for the blind (Hamid & Edwards, 2013). 3D-printing provides a low-cost solution to produce tactile maps. However, 3D-printed tactile maps must be designed and generated by a person that has expertise of computer-aided design (CAD) software and production techniques. Furthermore, the individuals creating the map would need to have knowledge of the appropriate map encodings, and parameters to design optimal tactile mobility maps. Additionally, determining which elements of an interior environment should be include or excluded and the stylization of the tactile map components is challenging (Touya et al., 2018). A mobility instructor, for instance, does not necessarily have the skillset or knowledge required to produce maps using these methods. If an individual does possess technical skills, the maps would most likely be designed using various styles since there is no standard set of symbology for tactile interior maps using 3D printing. This lack of understanding and standardization negatively impacts the users since they might receive various map types from different sources with widely varying styles and encodings.

Our goal is to provide an application that would automate the tactile map creation process enabling people to easily create and share 3D-printed tactile maps with the proper encoding system built-in. This required us to development of a custom map creator application. Similar research in this area has showed that individuals such as teachers would overwhelmingly use an application to create tactile maps for student with blindness and low vision (Lobben, 2005).

7.3 Audio-Haptic

When 3D-printing is not available a map might not be provided, or a different display method is used that does not fulfill the user's needs. An alternative to tactile devices maybe to provide Haptic feedback. Communicating structural content and graphical objects on a digital display without vision is the essence of what haptic feedback aims to accomplish (Corrigan, 2015).

Haptic properties have been described as both using a sense of touch, as well as producing or providing force feedback generated from the item to the sense of touch of the user (Kaplan, & Pyayt, 2015). A study conducted by Poppinga, 2011, showed positive results with vibration and audio to represent objects on web pages (Poppinga et al, 2011). Additionally, externalizations of mental representations were more accurate after using a prototype with audio and haptic feedback than after using a prototype with audio feedback alone (Yatani et al., 2012). There have also been attempts at haptic feedback applications and devices that have showcased positive results, however, they have not been widely adopted due to high costs, expertise needs to operate and setup, and limited shelf life (Kuber et al., 2014).

Most individuals with blindness and low vision use smartphones. In some cases, depending on the user the smartphone is modified with audio, haptic, physical keyboards, or other systems to allow for interaction (Young, 2013). Some research has been conducted using interactive 3D printed models. These models consist of 3D prints that have been modified with buttons, touchpads, cameras, sensors, motors, and audio devices. These types of interventions are limited in terms of accessibility since they require skilled experts to design and assemble. Furthermore, many of these models require a power source, and software updates depending on the complexity. They are also not customizable to a specific user's needs. There have also been Apps created specifically for this user population, as well as Apps that provide features that enable blind and low vision users to use them. For example, Digit-eyes can scan UPC code and provide audio descriptions of the produce (Wong, 2012).

Therefore, within the prototype map application, we decided to implement and test audio-haptic feedback using a mobile phone and tablet. The map generator application uses the same encoding conventions and interface as the 3D-printed tactile map, however, outputs an audio-haptic map. The audio-haptic map can be accessed on mobile devices such as smartphones and tablets through local files or using a modern internet browser. This additional audio-haptic map feature was incorporated in the development phase of the application and was user tested on smartphones with both congenitally blind individuals. The audio-haptic map creator has since been moved to its own web-based application since it was noted during testing that were differences in the specific tools and elements were needed that were not needed or used in the 3D-printed map application. For example, the 3D-print application limited the map size, whereas the audio-haptic map could be created without this limitation since a virtual map can be indefinitely extended.

7.4 Prototype Development

The Tactile Map Creator (TMC) is a web-based application that runs in any standard modern web browsers such as Chrome and Firefox. The application is built on Hyper Text Markup Language HTML5, JavaScript, and CSS. The application has two steps / interfaces that the user accesses during the map creation process. The first is the Drawing area, where the user designs and draws their 2D map. The Drawing area is automatically sized to the map required, e.g., single room or floor map based on the user's selection. The second area is the Generate 3D area, where the drawing is converted to a 3D model. The application interface uses custom-made Scalable Vector Graphics (SVG) icons representing doors, stairs, safe area, exits, and point-of-interest that can be dragged and dropped onto the Drawing Area (Kaplan & Pyayt, 2022) (Figure 7.1). The brushes tool is both a freehand and straight-line drawing brush and eraser feature that allows the user to create walls and paths. The brushes were developed with HTML 5 using canvas elements to render various line, and patterns for the walls, and evacuation paths. The application also includes a Guide tool to help the user measuring and layout the map elements. The guides are ignored once the user saves the map or generates the 3D model. There is also a remove guide and remove symbol option that will delete the newest placed symbol or guide. All these elements can also be placed outside of the Drawing Area and will be ignored during the save process. The application saves the users map as a Portable Network Graphics (PNG) file.

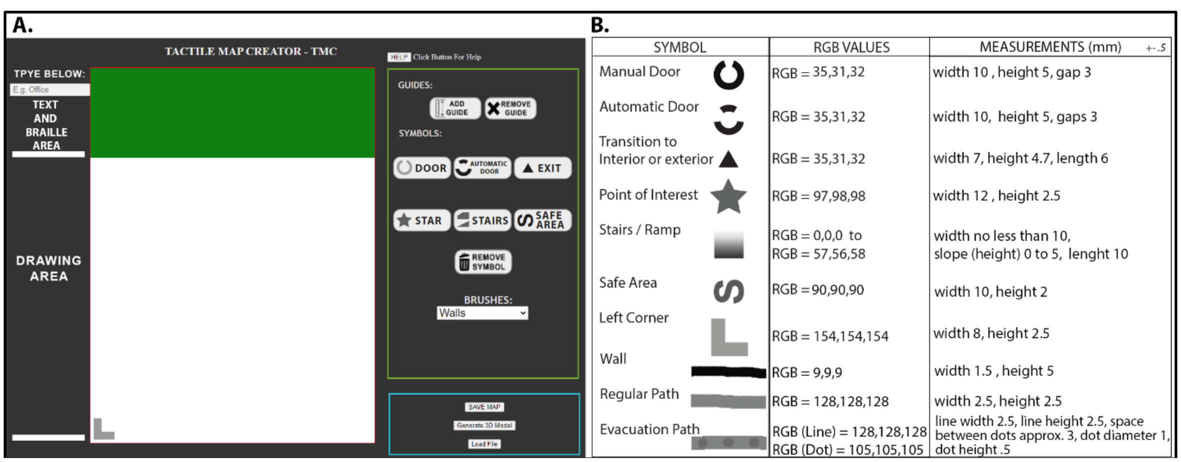


Figure 7.1 A) Tactile Map Creator 2D drawing interface. B) Symbols, RGB values and corresponding measurements.

The map drawing file can be shared and is also used to generate the 3D model. The Generate 3D Model feature uses the Three.js library and Web Graphics Library (WebGL) to create a 3D model using the pixel data of the map image. There are various methods for generating 3-dimensional models, such as using CAD, medical imaging, and 3D scanning (Pyayt & Kaplan, 2015). The Map Creator application uses a process where a high-resolution polygonal cube mesh is used to generate the 3D model from a 2D map drawing done in the application. This subdivided cube mesh allows for greater detail as image pixels can be correlated to vertex points on the mesh. The associated 2D image pixel data and cube mesh point locations can then be used to extrude and/or raise the points based on the 2D pixel information. The color image is converted to grayscale during this process, as color is not calculated in the 3D model, however, the pixel brightness is used to determine the extrusion height. This approach is computationally expensive as it requires significant processing to calculate large numbers of pixels perform the 3D extrusion levels. This means that this method has limitations with memory processing of high-resolution images that contain a large number of pixels. Once the 3D model is generated, it can be viewed virtual in the application 3D viewer and downloaded as a Stereolithography (STL) file for 3D-printing or further editing.

Within the Drawing area of the application is a text area. The user can type a room or map name, and the application will automatically provide the appropriate size, spacing and braille translation under the raised text version.

The application also provided the user with a premade braille and raised text map key that can be downloaded, 3D-printed, and provided along with the tactile map.

For this study, the tactile maps were 3D-printed using Fused deposition modeling (FDM) printing. Participants maps were printed on multiple 3D-printers including: Flash Forge Creator Pro, Makerbot Replicator, Monoprice Maker Ultimate, and MakergearM2.

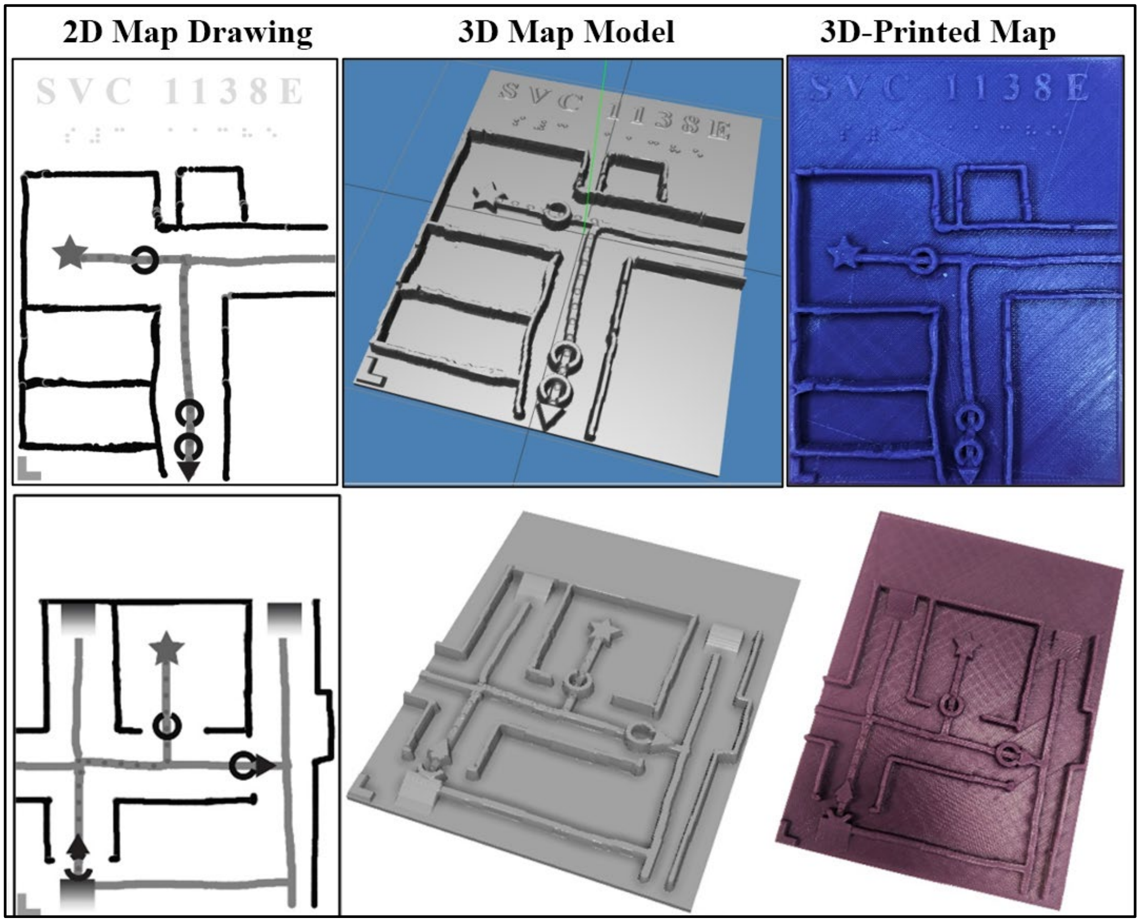


Figure 7.2 Participant 2D map drawings, 3D models and final 3D-print. All created using the TMC application.

7.4.1 Audio-haptic Features

The Audio-haptic Map feature allows the user to generate and save an HTML webpage that contains the map information that the user created in the Tactile Map Creator application. The application automatically converts the map from the Drawing Area of the application and places prebuilt Scalable Vector Graphics (SVG) elements representing the symbols, and areas into an audio-haptic webpage containing the interactive components and functionality for audio-haptic feedback. Some of the SVG elements are linked to premade Moving Picture Experts Group Audio Layer III (MP3) audio files that give the end-user verbal descriptions of the object, location, and direction they are touching and traveling across the smartphone screen with their finger. For instance, if the user's finger is over the stairs SVG, the audio file is called by the application, and the MP3 plays "stairs". Both the evacuation and normal travel path elements are linked to vibration functions that let the end-user know when their finger is on and off the path. When the user loses tracking, or their finger goes off the path the vibration stops.

7.5 User-testing and Features

Two studies were conducted for the prototype application. One was the usability-test of the application. This study required users to create maps using the Tactile Map Creator application. The study was done by ten participants (Table 7.1) including O&M trainers, subject experts, and health specialists. These types of users were chosen for the study because of their involvement with assisting the end-user group, and their knowledge of similar resources. The aim of the usability piolet test was to gather information about the features, output, and user-experience with the application. This testing and feedback provided us with a better understanding of the participants drawing and design process and the necessary features to incorporate or eliminate in the application.

A second study was also conducted to evaluate the output, of both the 3D-printed tactile map and the audio-haptic map generated from the application. Eight congenitally blind participants compared and provided feedback about the 3D-printed and audio-haptic maps.

7.5.1 Map Creator Application Testing Procedure

Both studies were conducted by researchers at the University of South Florida under IRB approval #00033464. The Tactile Map Creator application sessions were done with one participant at a time. Participants were seated at a computer with the application loaded and displaying the start screen. A ten-minute introduction of the application was presented prior to the participants using the application. A help section which described the symbols, tools, features, and techniques that could be used to create a map was also available to the participants to use at any time during the study process. A resource list in the application provided additional information about external 3D-printing services, online information sites and related software. Participants were then asked to create a map of a single room, and to include hallways (travel paths), emergency routes, doors, and exits. They were given as much time as they needed to create a map. The participants were also told to verbally communicate any likes or dislikes as they explored the application. Some of the participants used pen and paper to hand-draw the map first before moving to the application. All participants could ask question at any time during the mapmaking session. Each of the participants generated both Audio-haptic and 3D-printed tactile maps. The mapmaking session lasted no more than 40 minutes, with the quickest map being created in 15 minutes.

Table 7.1 Mobility and orientation trainers, and professional workers that tested the Tactile Map Creator application.

Gender	Age	Workplace	Ethnicity	Years of work	Level of technology
Female	49	Nurse Assisted Living Sarasota	White	12	(1) Beginner
Female	38	VA Health Science Specialist	Hispanic	8	(2) Intermmediate
Female	44	Research Health Science Specialist VA	White	13	(2) Intermmediate
Female	52	O&M Specialist South Eastern Guide Dogs	White	15	(2) Intermmediate
Female	46	USF College of Medicine	Asian	16	(2) Intermmediate
Female	22	Student College of Nursing	NA	1	(2) Intermmediate
Female	32	USF-Office of Students with Disabilities Services	Caucasian	3	(2) Intermmediate
Female	37	O&M Specialist Lighthouse Tampa	African American	6	(2) Intermmediate
Female	53	Health Specialist Researcher	White	15	(2) Intermmediate
Male	43	Disabilities Services	White	4	(3) Expert

After the participants exported the 3D map an online survey consisting of 45 questions on a 7 Point Likert scale was administered (Table 7.2). The Usability testing survey administered for this study is similar to other surveys that analyzed acceptance and use of technology for related products (Susanto et al., 2018). The survey is divided in to eight sections, to collect information about the participants: performance expectancy (PE), effort expectancy (EE), social influence (SI), facilitating conditions (FC), attitude towards using technology (ATUT), computer self-efficacy (CE), computer anxiety (CA), and behavioral intentions (BI), using the Tactile Map Creator. The survey type and test method are in line with other studies conducted to determine the overall effectiveness, use, and user acceptance and behavior towards technology resources (Lobben, 2005).

The surveys eight sections are outlined below:

1. Performance Expectancy – "the degree to which an individual believes that using the system will help him or her to attain gains in job performance."
2. Effort Expectancy - "the degree of ease associated with the use of the system".
3. Social influence - "the degree to which an individual perceives that it is important others believe that he or she should use the new system".
4. Facilitating conditions - "the degree to which an individual believes that an organizational and technical infrastructure exists to support use of the system."
5. Attitude toward using technology - "an individual's overall affective reaction to using a system."
6. Computer Self-Efficacy – "an individual's ability to learn and use the system independently."
7. Computer Anxiety – "an individual's emotional response in using the system."

8. Behavioral Intentions – "an individual's intended use of use the system." (Venkatesh et al., 2003; Lescevica et al., 2013)

Table 7.2 Tactile Map Creator application questionnaire

Performance expectancy (PE: 9 items)
1. Using a 3D printing map creator would enable me to accomplish given tasks more quickly.
2. Using a 3D printing map creator in my job would improve my performance.
3. I would spend less time in completing given tasks if using a 3D printing map creator in my job.
4. Using a 3D printing map creator would make it easier to do my tasks.
5. Using a 3D printing map creator would increase my chances of obtaining good evaluation in my works.
6. Using a 3D printing map creator would make me treat other coworkers as collaborators.
7. Using a 3D printing map creator in my job would increase my productivity.
8. Using a 3D printing map creator in my work would improve my effectiveness in completing tasks.
9. I would find use of a 3D printing map creator useful in my classes.
Effort expectancy (EE: 8 items)
1. Learning to use a 3D printing map creator is easy for me.
2. I find it easy to get a 3D printing map creator to do what I want it to do.
3. My interaction with a 3D printing map creator is clear and understandable.
4. I find a 3D printing map creator to be flexible to interact with.
5. It is easy for me to become skillful at using a 3D printing map creator in my works.
6. I find a 3D printing map creator easy to use in my works.
7. Working with a 3D printing map creator is complicated and it is difficult to understand what is going on. (Reversed)
8. It takes too long to learn how to use a 3D printing map creator to make it worth the effort. (R)
Social influence (SI: 5 items)
1. People who influence my behavior think that I should use a 3D printing map creator.
2. People who are important to me think that I should use a 3D printing map creator.
3. My co-workers in my workplace would be helpful in the use of a 3D printing map creator.
4. My co-workers would be very supportive of the use of a 3D printing map creator for my work.
5. In general, my workplace would support the use of a 3D printing map creator.
Facilitating conditions (FC: 5 items)
1. I have the resources necessary to use a 3D printing map creator.
2. I have the knowledge necessary to use a 3D printing map creator.
3. The 3D printing map creator is not compatible with other computer programs I use. (Reversed)
4. The technology support personnel (help desk) is available for assistance with 3D printing map creator difficulties.
5. Using a 3D printing map creator fits into my learning style.
Attitude toward using technology (ATUT: 5 items)
1. Using a 3D printing map creator in my workplace is a good idea.
2. I like working with a 3D printing map creator in my works.

Table 7.2 (Continued)

3. Using a 3D printing map creator in my works is pleasant.
4. 3D printing map creator makes my works more interesting.
5. Using a 3D printing map creator is fun.
Computer self-efficacy (SE: 4 items)
1. I could complete a given task using a 3D printing map creator even if there was no one around to tell me what to do.
2. I could complete a given task using a 3D printing map creator if I could call someone for help when I got stuck.
3. I could complete a given task using a 3D printing map creator if I had a lot of time to complete the task for which necessary resources were provided.
4. I could complete a given task using a 3D printing map creator if I just had built-in help facility for assistance.
Computer anxiety (ANX 4 items)
1. I feel apprehensive about using a 3D printing map creator.
2. It scares me to think that I could lose a lot of information using a 3D printing map creator by hitting the wrong button.
3. I hesitate to use a 3D printing map creator for fear of making mistakes I cannot correct.
4. A 3D printing map creator is somewhat intimidating to me.
Behavioral intention (BI: 5 items)
1. I intend to use a 3D printing map creator in the next 6 months.
2. predict I would use a 3D printing map creator in the next 6 months.
3. I plan to use a 3D printing map creator in the next 6 months.
4. I will use the 3D printing map creator on a regular basis in the future.
5. I will use the 3D printing map creator frequently in the future.

7.6 Tactile Map Creator Usability-testing Results

The results from the Tactile Map Creator usability-testing results are in agreement with the prior research that show a need for a software that enables users to create and provide tactile maps to people with blindness (Lobben, 2005). In every evaluated category the app performed really well.

7.6.1 Performance Expectancy Results

The Performance Expectancy data showed positive user feedback demonstrating that users of the application found that it would greatly improve their productivity and work efficiency (Figure 7.3).

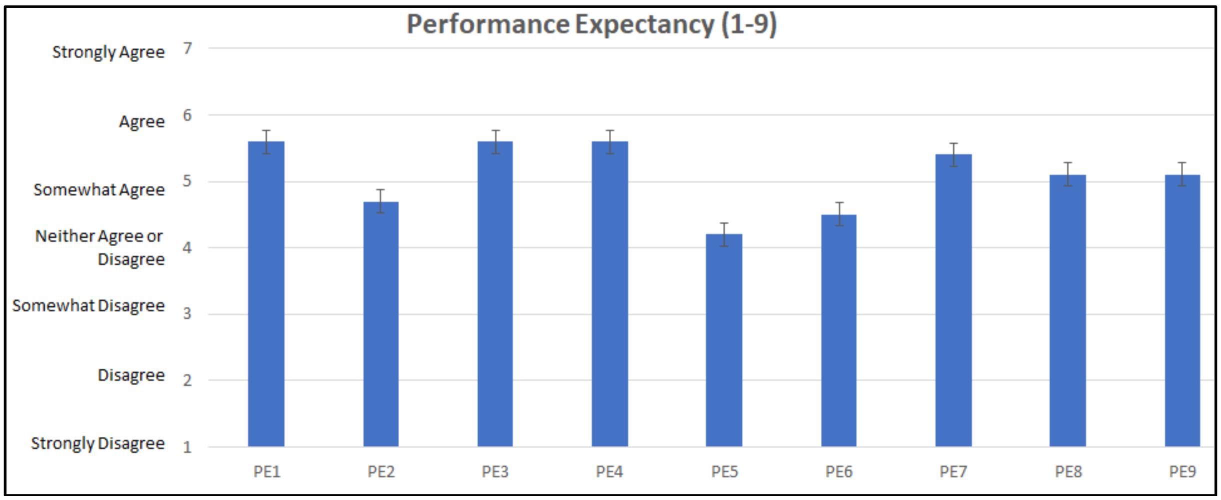


Figure 7.3 Bar graph of the Performance Expectancy data.

7.6.2 Effort Expectancy Results

The Effort of Expectancy results returned strong positive feedback showing that the users found that the map creator application was both easy to learn and easy to use (Figure 7.4). Therefore, the map creator was not found to be complicated to use or hard to learn for the participants.

7.6.3 Social Influence Results

User feedback from the Social Influence data showed positive results that participants agreed that co-workers would support the use of the Map Creator application in the workplace (Figure 7.5).

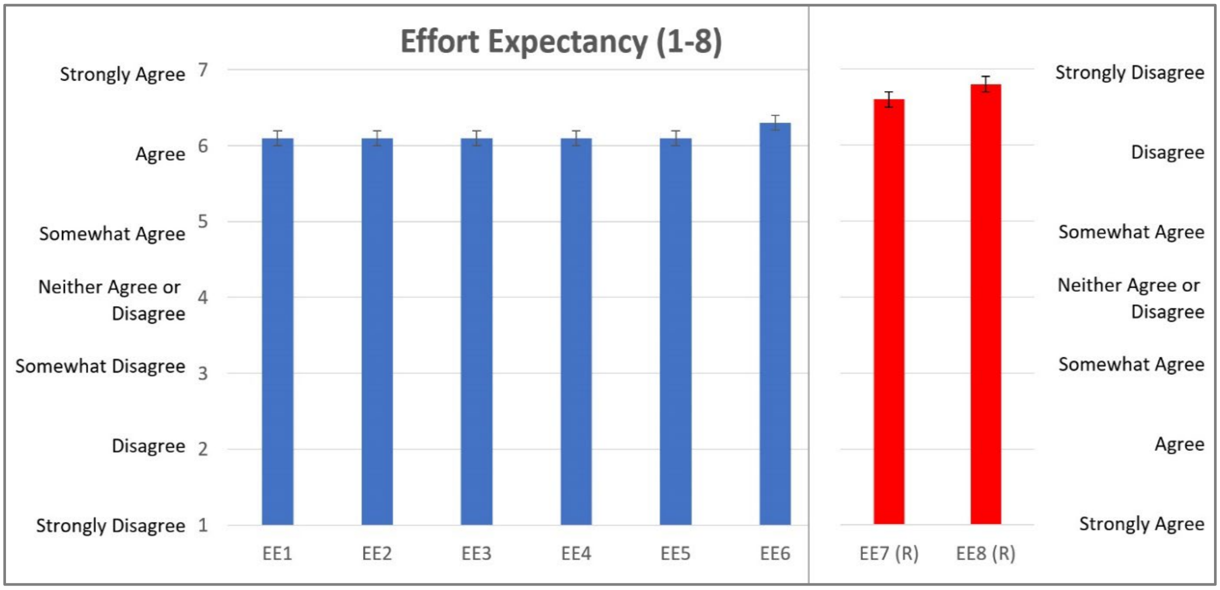


Figure 7.4 Bar graph of the Effort Expectancy data. EE7 and EE8 (in red) are reversed survey questions.

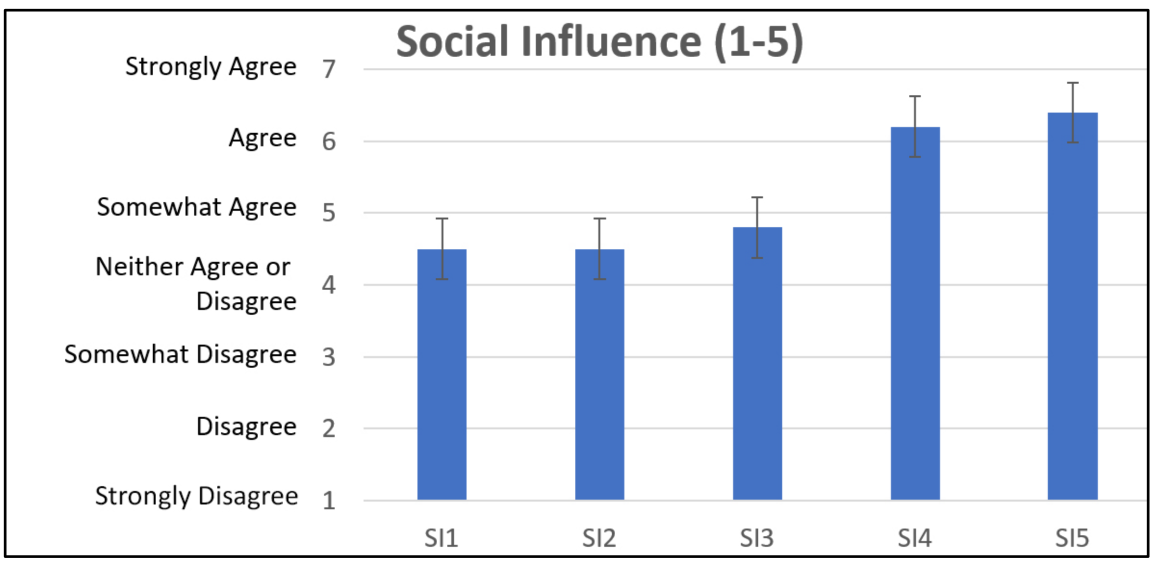


Figure 7.5 Bar graph of the Social Influence data

7.6.4 Facilitating Conditions Results

The results of the Facilitating Conditions portion of the survey displayed that all the participants have access to the resources, knowledge, and support that is necessary to use the map creator applications (Figure 7.6).

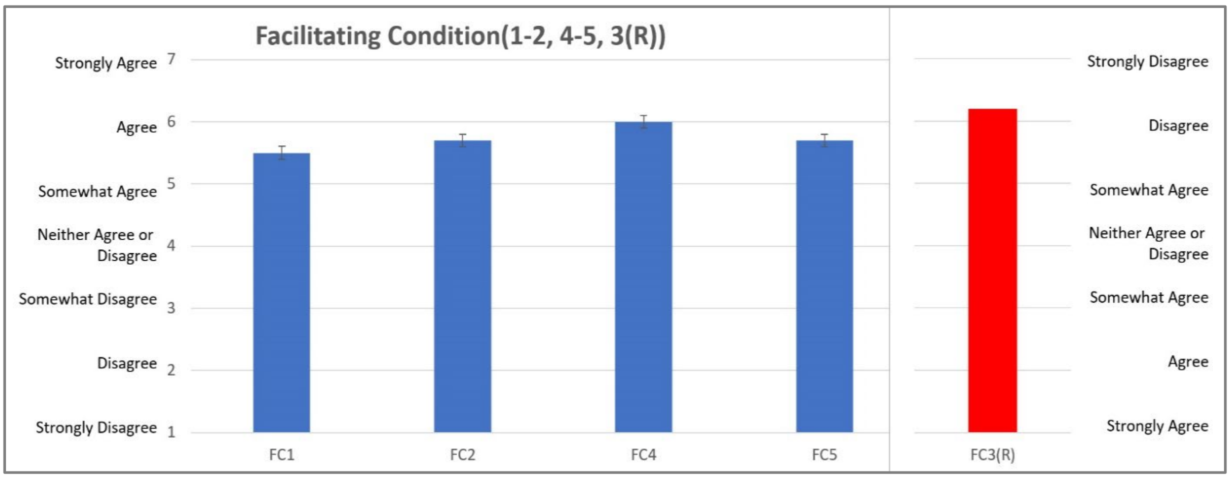


Figure 7.6 Bar graph of the Facilitating Conditions data. FC3 (red) is a reversed survey question.

7.6.5 Attitude Towards Using Technology Results

The feedback from the survey revealed that all the participants showed positive support and agreed or strongly agreed that the map creator application is fun and pleasant to use for their work (Figure 7.7). Therefore, they would most likely adopt this technology as a tool for their work tasks.

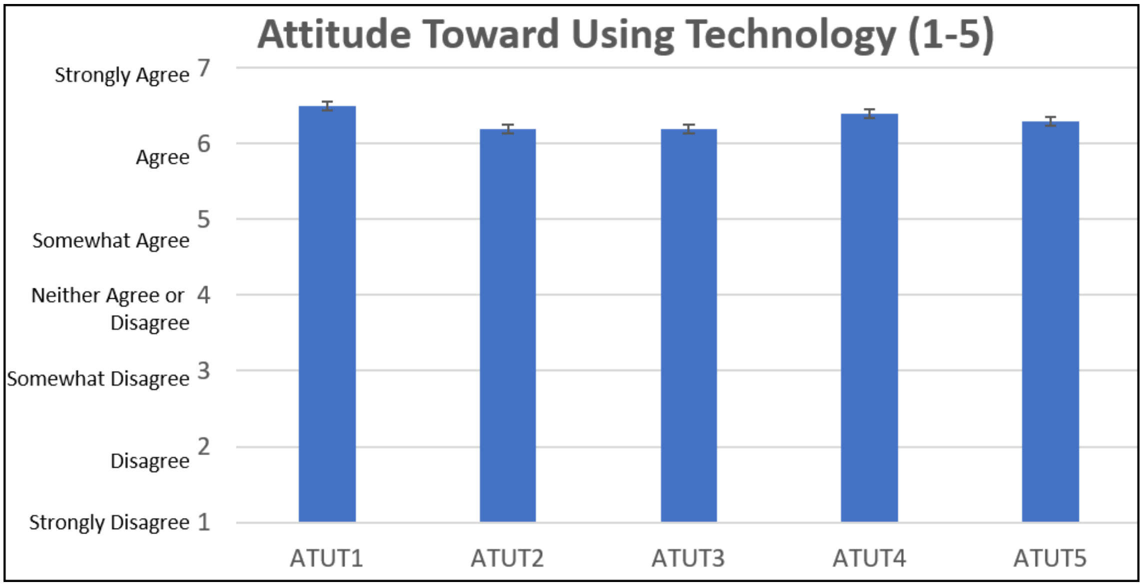


Figure 7.7 Bar graph displaying the results of the Attitude Towards Technology portion of the survey.

7.6.6 Computer Self-efficacy Results

The computer self-efficacy results demonstrate that the participants would be able to complete tasks using the map creator application both independently and with varying levels of support (Figure 7.8). This finding shows that users felt that they could use the application on their own, as well as with a built-in help feature, and enough time to complete the task.

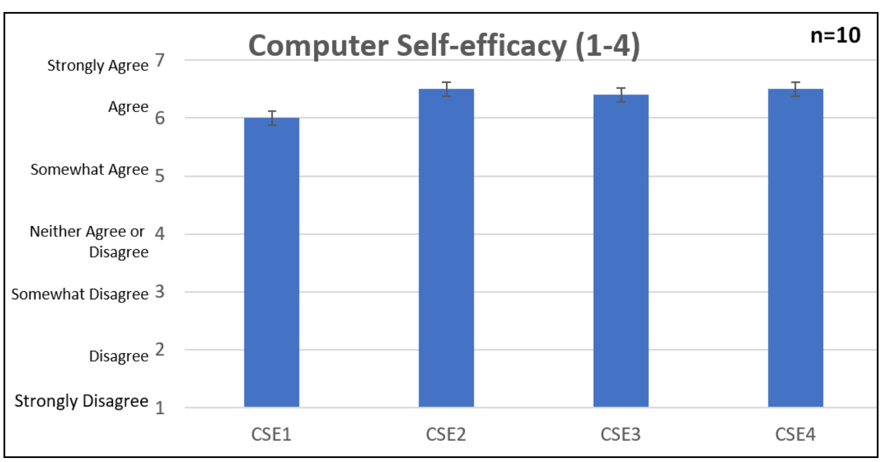


Figure 7.8 Bar graph showing the results of the Computer Self-efficacy portion of the usability survey.

7.6.7 Computer Anxiety Results

All the participants felt that using the map creator applications was not intimidating or scary. The participants were not afraid to make a mistake or apprehensive about hitting the wrong button while using the application (Figure 7.9).

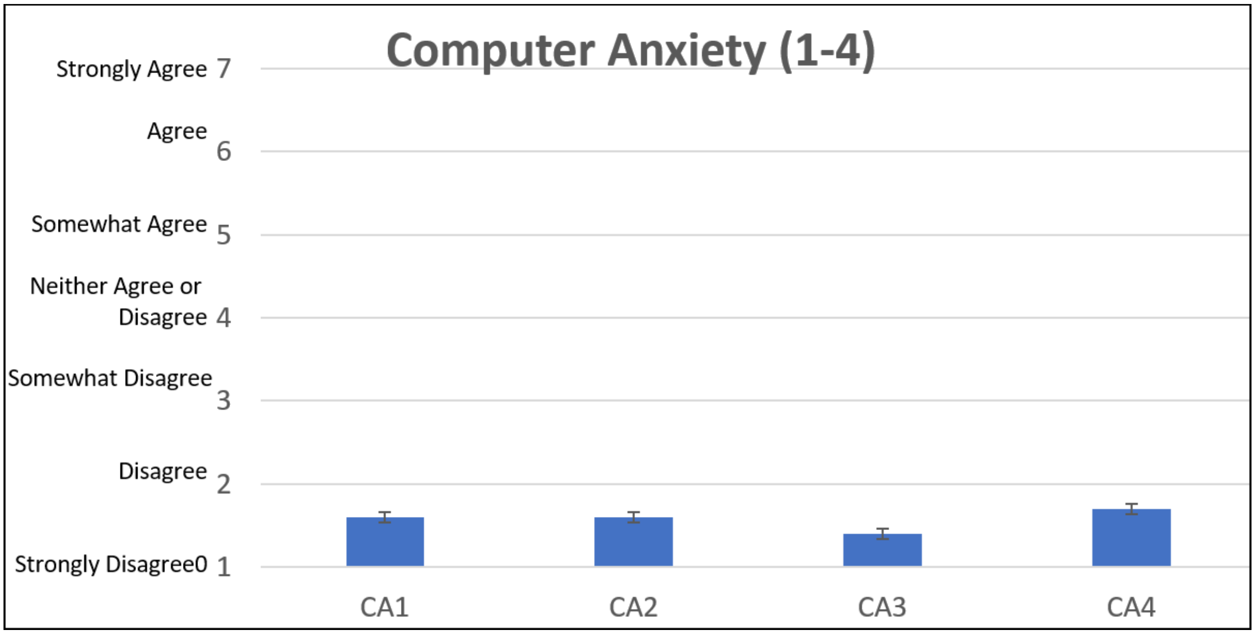


Figure 7.9 Bar graph showing the results of the Computer Anxiety portion of the usability survey.

7.6.8 Behavioral Intention Results

The usability survey Behavioral Intention section results showed that the participants intend to use the map creator application frequently and on a regular basis (Figure 7.10).

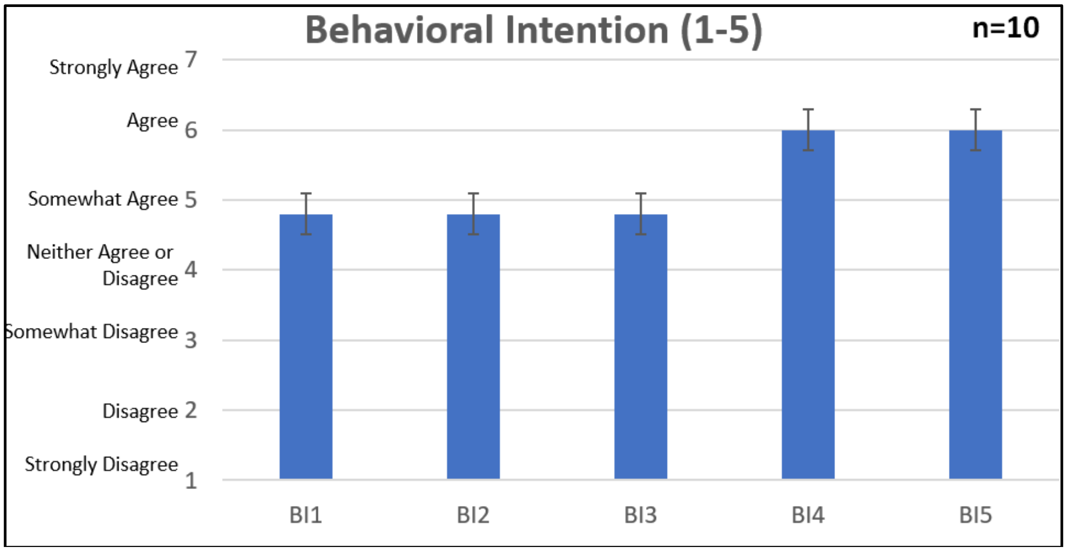


Figure 7.10 Bar graph showing the results of the Behavioral Intention portion of the usability survey.

7.7 End-user Testing of 3D-Printed Tactile and Audio-Haptic Maps

A small piolet test was conducted with eight congenitally blind participants to collect and analyze feedback about the maps produced by the TMC application. Three participants tested both the 3D-printed map and the mobile audio-haptic map, and five participants only tested the 3D-printed tactile maps. Each participant took part in the test individually and provided verbal feedback while using either the 3D-printed map or the audio-haptic map. The participants were asked to compare three versions of the map, two converted 2D drawn and 2D vector map, and a 3D CAD (Figure 7.11). The participants that used both types of maps, were given the 3D-printed maps first, and then the audio-haptic map on an Android smartphone, with the audio-haptic map already loaded on the screen (Figure 7.12). The study time ranged from 30 minutes to 1 hour, with an average study time of 43.5 minutes. The age of the participants ranged from 19 to 26, with an average age of 20.75. All the participants had experience using the 3D-printed maps from previous studies that we conducted on the optimized encodings.

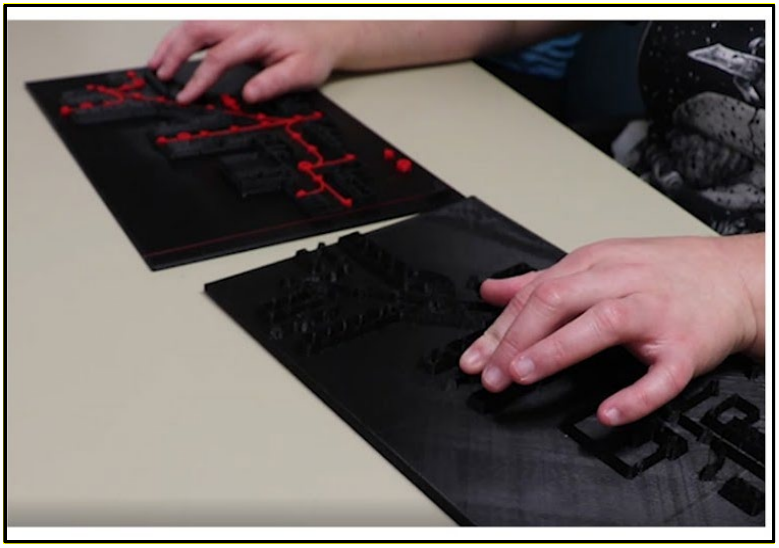


Figure 7.11 A participant comparing a map generated from the Tactile Map Creator application to a map created from CAD software.

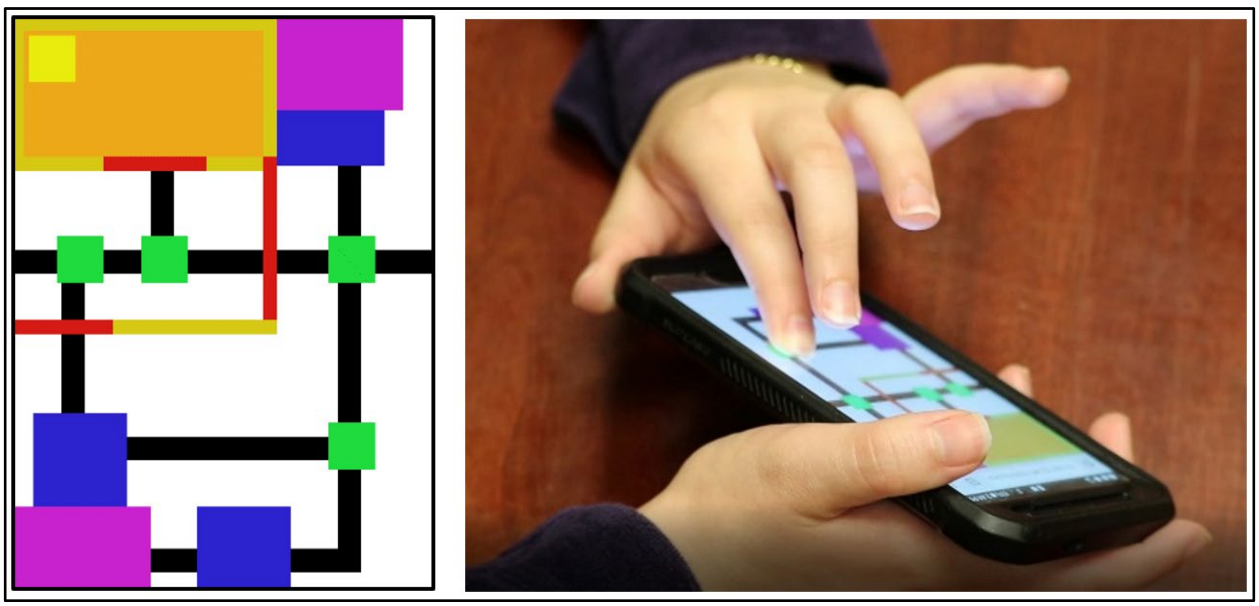


Figure 7.12 Left) Audio-haptic map generated from the Tactile Map Creator application. Right) Blind participant testing the audio-haptic map on a mobile phone.

7.8 Computational Comparison and Evaluation of 3D Map Model Quality

In developing the application, we wanted to generate maps that were of similar quality to the tactile maps that we manually 3D modeled using a CAD application and 3D-printed.

Since the 3D model in the TMC application is generated from 2D pixel data we tested, compared, and evaluated various 2D image types to find the 2D to 3D conversion type and process that produced a similar map quality as manually created optimized CAD maps. For, example a 2D drawing creates noise along the edges of the drawing that effect the output of the 3D mesh. Whereas, vector images, such as we used for the symbols in the application, create smooth lines and shapes that generate cleaner 3D meshes. Additionally, the pixel RGB data and resolution can both be controlled and balanced in application, as opposed to a drawing where a pen or pencil is used, and the drawing is scanned at a particular resolution.

To evaluate this further we explored the various mesh outputs of different methods, we used MeshLab and applied the Hausdorff Distance Sampling filter to compare the similarity of the results. This filter function compares the distance between all the vertex points across two similar meshes, in this case the CAD, and 2D converted models. The goal is to determine how well models or images match (Huttenlocher & Edwards, 2013).

Given two finite point sets: $A = \{a_l, ..., a_p\}$ and $B = \{b_l, ..., b_q\}$, the classic Hausdorff distance (CHD) is defined as:

1. $H(A,B) = \max(h(A,B), h(B,A))$
2. $h(A,B) = \max_{\mathbf{a}\in\mathbf{A}}\left(\min_{\mathbf{b}\in\mathbf{B}}(d(a,b))\right)$
3. $h(B,A) = \max_{\mathbf{b}\in\mathbf{B}}\left(\min_{\mathbf{a}\in\mathbf{A}}(d(b,a))\right)$

Using Meshlab, Colorize by Vertex Quality filter, we were able to analyze and visualize the sampling results. A jet color palette is used to represent the normalized Quality Vertex values, with red and blue colors used for high and low values, respectively. Higher Quality Vertex values are obtained where Hausdorff distance is lower. We ran the computation twice and analyzed the results of two versions of a 2D map, one hand draw with pen, and the other a 2D vector drawing. Both 2D drawings were similar to the TMC application were using shapes and lines that matched the 2D encodings. The 2D vector drawing was more similar since it also matched the TMC application with the use of vector graphics (Figure 7.13).

The results of the analysis showed that both versions of the 2D map provide similar topology as the 3D CAD model, however, the 2D vector map gave the best overall quality results. We determined that the 2D drawn map produced additional noise, resulting in sharp pointy edges when converted from 2D image to 3D mesh. Additionally, when the maps were 3D-printed the vector map produced a better-quality print than the 2D drawn map.

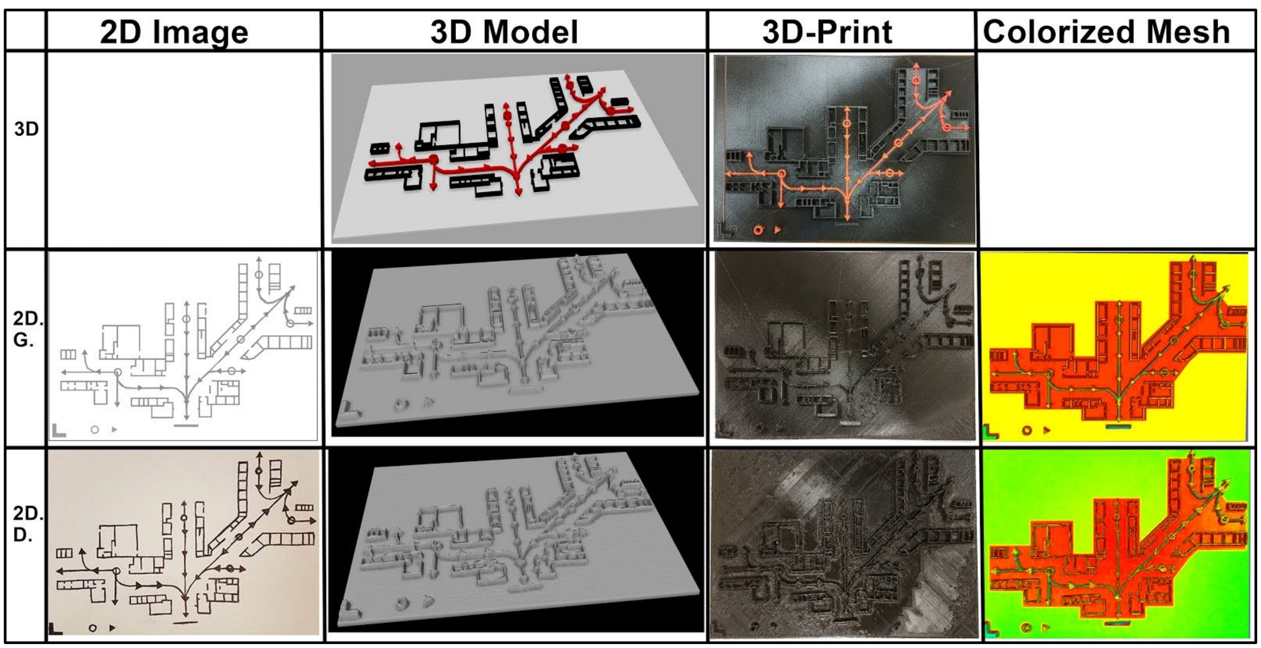


Figure 7.13 Comparison of 2D image to 3D models, and 3D-print. The results of the Hausdorff Distance Sampling Colorized visualization. The red color shows a small distance between points, while green and yellow represents a larger distance.

7.9 Conclusion Regarding Tactile Map Creator Application

Further work is needed in the development of the tactile map generator application. More user testing of the application is necessary to determine the ease and functionality of the application, especially with non-technical individuals. These tests will help to improve the applications data optimization and 3D model conversion methods, feature development and user-interface design. Furthermore, implementation of 3D-printing either on the user premises or through other means will need to be addressed. Additionally, the application needs to be deployed, benchmarked, and tested with various computer systems. This future work will help improve application accessibility, optimization, and compatibility.

7.10 Future Work

We are continuing to develop and test the Tactile Map Creator. As we explore and collect data on other tactile components, we will incorporate them in the application. We are also looking at other mapping alternative methods for producing and delivering tactile, audio, and haptic feedback and the user requirements that may impact developments or require a separate product. A 2015 study used an XBOX gamepad's high and low frequency motors to represent various colors to blind participants. The study demonstrated that the participants were successfully able to determine the right color through the vibration feedback of a gamepad (Trifãnică at el., 2015). Game developers have also utilized audio haptic feedback not only to enhance gameplay experiences for sighted individuals but also as accessibility features that allow blind and visually impaired game players enjoy the same video games as everyone else. Companies such as Microsoft have also explored Adaptive Controllers with a built-in Braille display (Coldewey, 2019). A paper published on the BlindAudio Tactile System (BATS) demonstrated the successful use of a Logitech Wingman Rumble gamepad by blind individuals on a virtual map of Roman Britain (Parente & Bishop, 2003), where haptic vibrations were implemented using the Python programming language to represent state and county boundaries. Studies have shown that using both audio and haptic feedback can benefit cognitive skill specifically orientation and mobility (Espinoza at el., 2014). Additional Research of haptic visualizations for charts, networks, and maps has highlighted the role that constraining the user by haptic feedback can in benefit the users understanding of the structure being represented on the display (Paneels & Roberts, 2010). Other studies have also made recommendations for evaluating and implementing multimodal application features for blind and visually impaired users (Darin at el., 2019).

7.10.1 Audio-Haptic Map Creator Application Description

As mentioned previously, we have begun developing and testing a separate Audio-haptic Map Creator application. This application is still in the early phases of development. The maps created with this application, like the TMC application, are for blind individuals to use prior to visiting a location so that they can learn and possible plan their visit. We are exploring this area as an alternative to 3D printing, as this method may allow maps to be shared quicker. Also we use different input/feedback interfaces due to the limitations of touchscreens, i.e., the ability to move your figures beyond the boundaries of the screen, as well as the limitations of the touchscreen ability to allow multiple or simultaneous interface interactions (button presses) while also providing haptic feedback. The screen size also limits the area and number of elements that can be displayed on a map, as well as the relationship between the user's figure and those elements. As a result, we are currently in the process of user-testing the application and the end-user audio-haptic maps created by the application with various gamepads that have vibration capabilities to allow for additional functionality and control to enable more interactivity, and larger mapped areas that could result in more information delivery to the end-user.

7.10.2 Audio-Haptic Map Creator Application Development

The Audio-haptic Map Creator Application was developed using HTML5, CSS, and JavaScript. HTML5 is used to provide the main visual display feedback to the user and is where the main application functions. CSS is used to style the application such as the colors, margins, and layout. JavaScript is used to provided functionality and that provides HTML and CSS the proper display based on the user input, (mouse, keyboard and/or gamepad).

The application runs in most modern browsers that support the necessary Gamepad API functions (Gamepad API, 2021). The Gamepad API provides a way for web applications to directly interface with gamepad data. The low-level implementation allows for programming that provides access to hardware features. With the recommended browser being Google Chrome (Gamepad, 2021), and the recommended gamepad being XBOX 360 (Figure 7.14). However, most generic USB gamepads will work (Nyman, 2019). The audio-haptic application requires gamepads that have motors for vibration capabilities, referred to as rumble motors (Figure 7.15). We have successfully used the XBOX 360, GameSir G3s, and PlayStation gamepads.

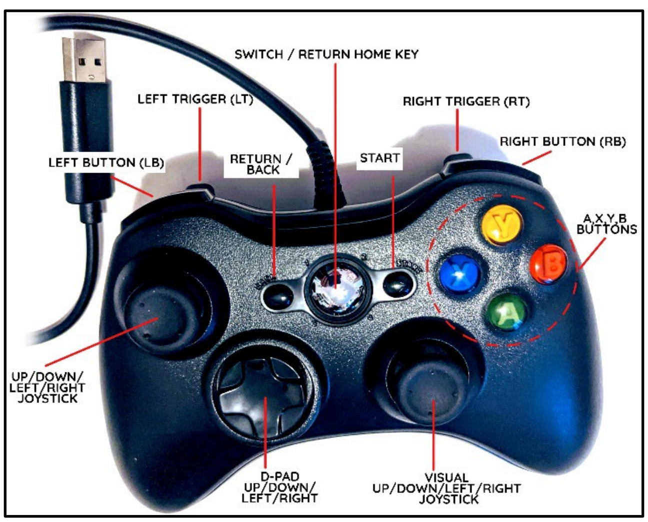


Figure 7.14 XBOX 360 gamepad.

There are two input types that are used to provide user input, buttons, and axis. However, some browsers such as Firefox and Safari currently do not support some of the functions required for this application such as hapticActuators which represents haptic feedback hardware and allows interfacing with the gamepad motors. The Audio-haptic Map Creator application uses JavaScript to query input and supply functionality to and from the application and gamepad device. User interactions with the buttons and joysticks are determined using JavaScript which also provides the functions that set the display in the HTML5 Canvas, and/or through the vibration of the gamepad motors. Currently the API haptic functions support “dual rumble” meaning both motors, vibration duration in milliseconds, start delay which is the delay time in milliseconds before the effect, and Strong and Weak Magnitude which sets the low and high frequency of the motors. However, the magnitude in the Gamepad API is set from 0 to 1 and not in Hertz.

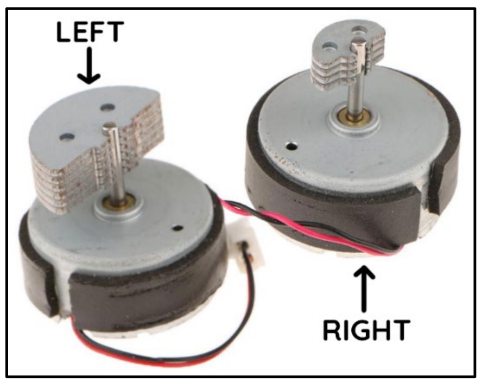


Figure 7.15 Standard gamepad motors and weights.

The application also uses the web browsers native text-to-speech API. The application allows users to add text to their map, and when the user travels over the text a JavaScript functions calls on the API SpeechSynthesis to automatically read the text data as audio.

Another import aspect of the application is that it can be used from and saves the map data completely on the client side. When the user is finished creating their map they can save the entire application, to their computer, including their map they created. They can then share it and/or edit it later by opening it in the browser. The elements positions are all stored in the HTML document itself, including the paths data. This was achieved using SVG polyline and JavaScript drawLine which stores the 2D point coordinates (x,y positions) of the line.

7.10.3 Audio-Haptic Map Creator Application Interface

The application is under development; however, the current interface acts as both the Map Creator and end-user interface. This makes it so that the creator map does not need to be further processed and converted to an end-user interface. Additionally, this combined interface makes it easier for the individual that might be helping the blind user to make edits to the map on-the-fly. The interface has three sections that can be seen in Figure 7.16. First, the Title Area, this provides text information related to the gamepad buttons, and application version. The next section is the Map Area, it is where the map is created by placing and drawing map elements selected from the Menu. This area is also where the user would interact with the map using the gamepad. The red circle in the Map Area represents the user's location on the map and is controlled with the gamepad left toggle/joystick. When a user with blindness interacts with the gamepads joystick the red circle moves. Even though the user does not see this, the red circle is used to assist the map creator in building and testing the map. The red circle is part of the HTML Document Object Model (DOM) tree as a Division (DIV) element. When the user DIV crosses over other elements, such as the path, the application triggers a function. In the case where the user DIV passes over the path JavaScript calls the vibrate gamepad function and provides haptic feedback to the user that they are currently on a path. Figure 7.17 shows the flow of the user input and corresponding DIV and JavaScript process. Other functions in the application trigger audio or reposition the user on the display.

The third section is the Menu located on the right-side of the application it contains all the tools and features needed to create and save a map. The Menu can switch between visible and hidden by pressing the "~" on the keyboard.

The Menu allows the user to determine a start position by clicking and dragging the "Star" icon to the Map Area. When the user presses the "A" button on the gamepad they are automatically repositioned to that point.

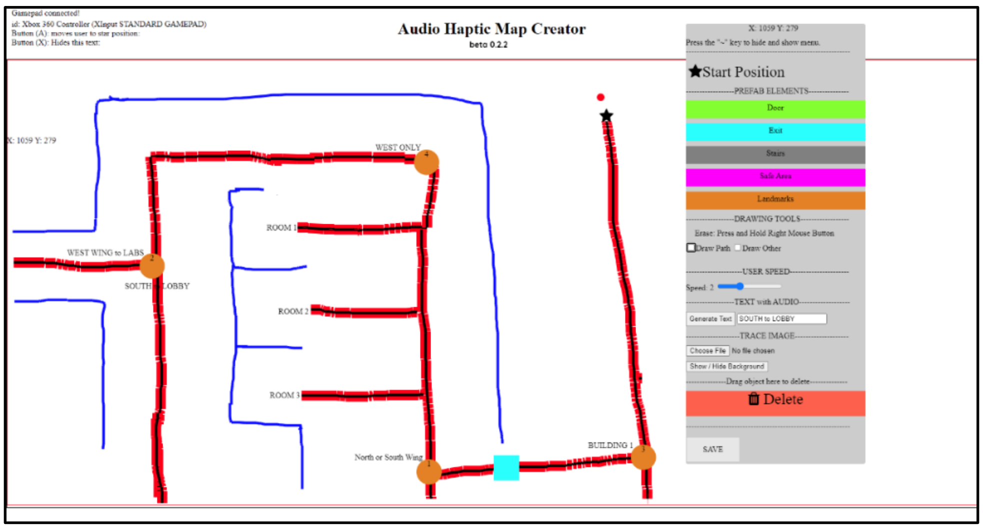


Figure 7.16 Audio-haptic Map Creator interface. Top: Title Area, Center: Map Area and Right; Menu.

There are predefined "Prefab Elements", "door", "exit", "stairs", "safe area", and "landmarks", that can be selected and dragged anywhere in map area. These prefabs define an area on that map that represents that elements label. All these elements, except for the landmarks, also have audio attached to them that will automatically play when the user moves over or near them. The landmarks elements allow the map creator to define points on that map that can be used to help user determine where they are relative to other points on the map. Each time the user presses the "Right Trigger" on the gamepad they are repositioned on the landmark point. It is recommended that the map creator place the landmarks and then use the Generate Text feature to provide an audio description of what the landmark represents.

There are two drawing tools that can be used by clicking the checkbox and holding and dragging the left mouse button to draw in the Map Area. The first is the Draw Path tool, this used to describe the travel routes, and sets the gamepad vibration when the user travels along the path. The second is Draw other can be used by the map creator to plan out and draw other map items such as walls and areas that cannot be used for travel. We are in the process of developing audio zones that increase or decrease in volume as the user get closer or further away from the zones. For example, if a user gets closer to a wall, street, or parking lot the audio zone will trigger the sound of cars increasing as the user move further into that area. Both Drawing tools can be erased by pressing and dragging the right mouse button over the path lines in the Map Area. The Menu has a Speed Slider that allows the user to adjust the Map Indicators travel speed on the map. Speed 1 is approximately 70px per second. The Generate Text feature is used to write and place text anywhere on the map that will automatically play audio reading the text when the user passes over it. Since there may be a delay playing text audio, especially when using multiple text elements, it is recommended that there be approximately 100px between text elements at a speed setting of 1. However, this may vary depending on how much text is used in each single element. For example, a single word will play faster than a sentence. The user can mute and unmute the audio by pressing the “Y” button on the gamepad. We are planning adding other interactive features to the map that interface with the gamepad, such as using a button when reaching the “Stairs” element to be able to load and switch between different floors of a building.

Trace Image can be used by the map creator to upload an image from their computer to the Map Area and use it as a guide to help them draw a map. This image can be displayed or hidden by pressing the Show/Hide Background button. Draggable objects such as Prefab Elements and Text can be deleted by dragging then to the Delete Area on the Menu. Finally, the Save button allows the map and all the features to be saved on the user's computer as an HTML file.

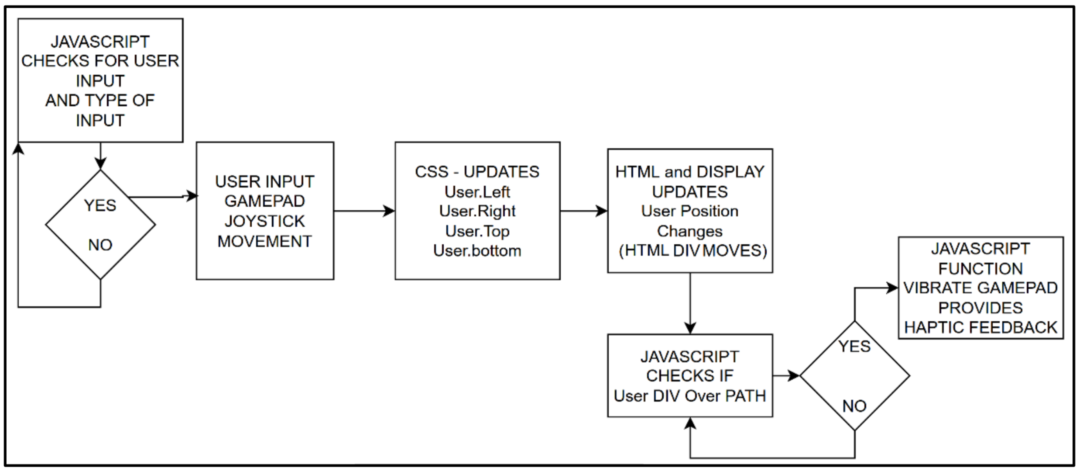


Figure 7.17 Diagram of application user input example function and feedback process.

7.11 Conclusion

In the future studies of the audio-haptic maps, more work is required to determine the size limitations regarding the digital display type, (i.e., smartphone or tablet), the style of maps that can be provided (i.e., single room or floor map), and the appropriate audio and haptic cues to use for communicating various spatial components. Additional studies will be used to determine appropriate haptic feedback of the vibration capabilities and map elements sizes. Most modern cellphones vibrate between 130Hz and 180Hz. Furthermore, there are both hardware and programming interface limitations between various phone manufactures, platforms, and web applications. For instance, Android and iOS uses different vibration functions, and Firefox, Chrome, and Safari support various types and levels of vibration output. Additional development and testing will help to inform us on how to best provide map information to the end-user within the limitations of mobile phones, given that audio, and vibration are the only feedback functions that can be used by a person with blindness or visual impairments.

Using the additional hardware, gamepad, we were able to extend map features and capabilities, however, more user-testing will allow us to determine the usability of these added components and features need for both the map creator and the end-user. The audio-haptic map can be used with a gamepad on desktops, laptops, and mobile devices via USB and/or Bluetooth to provide haptic vibration feedback and interactivity. When using the extended map with a gamepad the map area can be greatly increased, since there is no boundary as there is with the touch version. When using the map with touch the user is limited to the size of the phone screen as applying a scrolling feature can cause the user to lose their place on the map (path). Therefore, the current touch maps are restricted to the edge of the phone screen. However, with a gamepad controller this can be expanded since the toggle / joystick is used to move the user along the map and path, not the users finger. This allows the user to go beyond the phone screen and continue almost infinitely. Additionally, using the various buttons on the gamepad will allow the user to identify and navigate to different points of interest and landmarks such as buildings, stairs, different floors within a building, multiple rooms, and bus stops. However, more information needs to be evaluated on the use of a gamepad by people with blindness, specifically the speed of the map, gamepad input and output functions for information delivery, and user preference. Once these additional integrations have been user-tested and evaluated we will implement them into the Audio-Haptic map creator. We foresee these developments happening in an iterative process consisting of feature development, user-testing, and feedback.

Chapter 8: Summary

Tactile maps are vital resources for people with blindness and low vision, and as such, they need to be properly designed, and made accessible to all in this user population. The research presented in this dissertation demonstrates that a well-developed tactile map not only allows the user to develop an awareness of spatial elements and navigation routes but helps to generate metal model of their relationship to the environment. Using the tactile maps developed for this research people with blindness and low vision were able to read, understand and use information communicated by the map encodings and system to build spatial awareness and understanding of structural and navigational elements that resulted in improved orientation and mobility. Using the tactile maps participants created mental models of the environment that they used to mentally map-out information connecting rooms, hallways, doors, and other architectural landmarks in a sequential manner to plan travel routes. By implementing a user-centric approach for testing and development an optimized encoding system was created that enabled the target to efficiently read and comprehend the maps, and practice safe and independent mobility.

The tactile map production process will advance as 3D-printing technology continues to improve with the ability to print greater detail, more material types, control quality, and obtain quicker production speeds. Although, 3D-printing may not be the only production method for these types of tactile maps. Other production methods and processes could be used when access to 3D-printing is not available, however, the encoding system and parameters presented should be followed regardless of the medium used.

Adoption and use of the symbols are a critical next stage. Two key steps have been taken to encourage widespread use of the symbols. First, we have disseminated the symbol set to key organizations serving blind and low vision population. This research has been shared with a wide audience and disseminated in publications, media outlets, and conferences (Kaplan & Pyayt, 2019). Major organizations such as Path to Literacy, for students who are blind and visually impaired, have published, and freely shared this research as part of their toolsets and resources to the community (Cushman & Tabb, 2018). We have also conducted on-site workshops with some of these organizations, such as Southeastern Guide Dogs, and Tampa Lighthouse, and will conduct more soon. This distribution by a leading authority increases dissemination of the symbol set to authentic users.

Overtime, we believe that the maps will become more standardized in terms of implementation, acceptance, and utilization. Our development of the Tactile Map Creator application will help to further drive the implementation and use of these maps. Second, the optimized encoding system has and will continue to help future mapmakers in the design, development, testing, and implementation of assistive technology for people with blindness and low vision as non-technical individuals will be able to use the encoding system, and Tactile Map Creator application to build custom maps of their own. Furthermore, individuals will be able to use the information that we have shared to design new encodings and maps that build on our work. We will continue to expand on this research and generate new findings that benefit this community.

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The permission below is for the use of images for Figure 2.1 and 2.2.

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December 6, 2018

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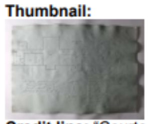

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Sincerely,

[redacted]

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2/19/2018

Howard Kaplan
Research Computing
4202 East Fowler Ave
Tampa, FL 33620

RE: **Expedited Approval for Initial Review**
IRB#: Pro00033464
Title: 3D Printed Tactile Visualization

Study Approval Period: 2/19/2018 to 2/19/2019

Dear Mr. Kaplan:

On 2/19/2018, the Institutional Review Board (IRB) reviewed and **APPROVED** the above application and all documents contained within, including those outlined below.

Approved Item(s):
Protocol Document(s):
Protocol Maps

Consent/Assent Document(s)*:
Consent Form.pdf

*Please use only the official IRB stamped informed consent/assent document(s) found under the "Attachments" tab. Please note, these consent/assent documents are valid until the consent document is amended and approved.

It was the determination of the IRB that your study qualified for expedited review which includes activities that (1) present no more than minimal risk to human subjects, and (2) involve only procedures listed in one or more of the categories outlined below. The IRB may review research through the expedited review procedure authorized by 45CFR46.110 and 21 CFR 56.110. The research proposed in this study is categorized under the following expedited review category:

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

Your study qualifies for a waiver of the requirements for the documentation of informed consent as outlined in the federal regulations at 45CFR46.117(c) which states that an IRB may waive the requirement for the investigator to obtain a signed consent form for some or all subjects if it finds either: (1) That the only record linking the subject and the research would be the consent document and the principal risk would be potential harm resulting from a breach of confidentiality. Each subject will be asked whether the subject wants documentation linking the subject with the research, and the subject's wishes will govern; or (2) That the research presents no more than minimal risk of harm to subjects and involves no procedures for which written consent is normally required outside of the research context.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval via an amendment. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) calendar days.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

[redacted]

Kristen Salomon, Ph.D., Vice Chairperson
USF Institutional Review Board