Usable Accessibility and
Haptic User Interface Design Approach

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ABSTRACT

Many people have visual impairment and make up a population that is increasing each year. Haptic technology is often used to assist members of this population by providing a way of understanding visual information. Although haptic technology is relatively new, it is widely applied across a variety of domains (research and industry). However, a great number of users are dissatisfied with their assistive technology applications. Unfortunately, such dissatisfaction is likely to cause abandonment of the technology devices. In particular, recent research shows that the adoption rate of haptic technology is low. Discontinuing the use of assistive technology devices ultimately results in a waste of time, money, freedom, and reduced function for individuals with disabilities. Of all the factors that lead to abandonment, the most significant is the failure to meet user needs. Whether existing design approaches properly reflect assistive technology user needs should be explored, especially for haptic technology.

Existing design approaches have rarely considered the heterogeneous needs of users in the same disability category (i.e., visual disability). Most previous studies on assistive technology have been oriented towards those with total blindness as opposed to those with residual vision (also referred to as low vision). In addition, researchers have paid less attention to older adults with low vision in terms of individual differences in haptic user interface (HUI) needs. There is also some doubt about the applicability of existing design approaches in such design contexts as users with visual disabilities using haptic user interfaces.

The aim of this research was to investigate individual differences in users' capabilities in the haptic modality and user needs in HUIs. Particularly, age-related and vision-related individual differences were explored. Another aim was to develop a more accessible design approach applicable to users with visual disabilities and HUIs.

The magnitude estimation technique was employed to examine how participants (classified by vision and age) perceive the same objective stimulus, such as haptic perception, differently. Brain plasticity theory was primarily applied to modify the existing design approach, PICTIVE. The effectiveness of modified and original PICTIVE methods was investigated in terms of the frequency of statements, gestures, satisfaction, and time to complete a given design task. HUI user needs were elicited from participants and were analyzed to understand age-related and vision-related individual differences.

It was found that the haptic perception of the same objective stimulus was not significantly different between younger and older participants with low vision. The two age groups' overall preferences for a set of HUI user needs were not significantly different. In addition, the haptic perception of the same objective stimulus was not significantly different between sighted participants and those with low vision. The two vision groups' overall preferences on a set of HUI user needs were not significantly different as well. The two design methods resulted in significantly different outcomes. First, participants in the modified PICTIVE method made a significantly higher number of statements. Second, participants in the modified PICTIVE method showed a significantly higher number of gestures. Third, participants in the modified PICTIVE method took significantly more time because they had more design ideas to deliver. Last, both groups were satisfied with a given design method.

In short, the research outcomes contribute to the advancement of knowledge and understanding of more "usable" accessibility for users with visual impairment and a more "accessible" participatory design approach to nontraditional user interfaces (i.e., haptic user interfaces) for users with visual impairment.

DEDICATION

I dedicate this dissertation to my family.
Thanks for all your support.

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CHAPTER 1. INTRODUCTION

This introduction offers an overview of this research. A more detailed discussion is located in the literature review section.

1.1. Background

Approximately 45 million people worldwide are blind, and this number increases by 1-2 million each year (National Institutes of Health, 2002; West & Sommer, 2001). Every 7 minutes, an individual in the U.S. becomes visually impaired or totally blind (Mroczka, 2005). Furthermore, the American Foundation for the Blind (AFB; 2008) estimated that there are approximately 1.3 million people in the U.S. who are categorized as legally blind and have a visual acuity of 20/200 or less in the better eye with the best correction possible.

Contrary to common perception, the majority of people who are visually impaired have residual vision (or low vision) rather than total vision loss. Unfortunately, most of the literature on assistive technology has been oriented towards those with total blindness rather than those with low vision. In fact, there are almost three times as many people with low vision than people with total blindness (Jacko, J., Scott, L., Sainfort, F., Moloney, K., Kongnakorn, T., Zorich, B., and Emery, K., 2003). Moreover, low vision is more common among the elderly (aged 65 and older) because of age-related vision sensory degeneration, and the number of individuals aged 65 and older increased to more than 34.6 million in 2000 compared to 3.1 million in 1990 (US Census, 2000). Furthermore, the elderly are likely to become a significantly larger proportion of the population by the year 2020 (Dewsbury, Sommerville, Bagnall, Rouncefield, & Onditi, 2006). According to the U.S. Census Bureau (2005), the population aged 65 and over is anticipated to grow from 35 million to 86.7 million between 2000 and 2059 (see Figure 1). Of people with visual impairment, two-thirds are over the age of 65 (Ross, 2004). The number of older adults with visual impairment will increase dramatically in the future (Burggraaff, Nispen, de Boer, & van Rens, 2006). Consequently, the role of assistive technology will be increasingly important in the future.

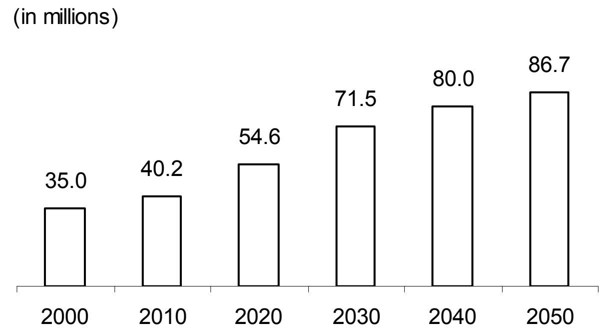


Figure 1. Projected growth of the older population, aged 65 and over, between 2000 and 2050 (U.S.Census Bureau, 2005) [public domain]

The effectiveness of existing assistive technology applications remains in doubt. Braille has been regarded as the primary tool for people with visual impairment to use in obtaining information. However, Braille is based on a low-tech display, such as paper and dots, which is likely to result in limitations in the presentation of visually complex information (e.g., waves, webs, shadows, cycles, color, and coils). Presentations of tactile graphs face challenges in terms of the level of sensitivity, resolution, graph complexity, and array (Ebina, Lgi, Miyake, & Takahashi, 1998). Besides the technical challenges, maintenance issues (e.g., hygiene and durability) are also of concern (Yu & Brewster, 2003). Furthermore, only a small number of individuals who are visually impaired can read Braille, and the population has been decreasing. For example, less than 10% of people with visual impairment in the U. S. can read Braille (Petrie, Morley, McNally, O'Neill, & Majoe, 1997). Instead, most use computer-based assistive technology applications, such as screen-reading software (e.g., JAWS, VoiceOver, and Dragon Naturally Speaking). Through screen-reading technology, information is obtained more effectively, and learning Braille is no longer required. The Internet offers a great deal of information, even to those who are visually impaired. Nevertheless, a barrier remains in accessing information that is graphically oriented. Typically, screen-reading technology recognizes “information in text” and reads it aloud (Aldrich & Parkin, 1998; Yu, Reid, & Brewster, 2002), but auditory description cannot effectively convey “information in images” to users who are visually impaired (Aldrich et al., 1998; Yu et al., 2002). Furthermore, the process of navigating is tedious because of the linear output of screen-reading technology without overview (Kuber, 2006).

Currently, haptic technology is often used to represent complex graphic-based information. The term "haptic" commonly refers to the sense of touch. More specifically, the haptic sense consists of cutaneous touch and kinesthetic touch (Kortum, 2008; Sallnas, Rassmus-Grohn, & Sjostrom, 2000; Sjostrom, Danielsson, Magnusson, & Rassmus-Grohn, 2003; Smith, 1997). Cutaneous touch is related to the sensations felt on surface features and tactile perception, which is conveyed via the skin. On the other hand, kinesthetic touch is part of the haptic sensations that involve muscles and tendons, which enable people to recognize the movements of limbs. The sense of haptic is influenced by both the cutaneous touch and the kinesthetic touch. A haptic device interacts with virtual reality interfaces that users manipulate to receive mechanical feedback (e.g., vibrations) from two-dimensional or three-dimensional objects (e.g., images and graphs). The haptic interface is supported by a real-time display of the virtual environment, in which users can explore a virtual object by pushing, pulling, feeling, and manipulating it with a device (e.g., mouse, stylus). Users are able to experience simulations of various properties of objects, such as mass, hardness, texture, and gravitational fields. Haptic technology is relatively new, but is widely used across a variety of domains, including the automotive, cellular phone, and entertainment industries; education, training, and rehabilitation; controls and assistive technology development, and medical science; and the scientific study of touch (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004; Kortum, 2008). For example, 2,000 medical simulators with haptic technology have been sold worldwide to hospitals and teaching institutions to train clinicians (Immersion, 2008). Additionally, haptic technology is embedded in mobile phones to enhance user experience. As of September 2008, over 25 million mobile phones featuring haptic technology were sold worldwide, with 7 million sold in the second quarter of 2008 alone (Ayala, 2008). The use of haptic mobile phones had more than doubled over the previous quarter.

The question is whether haptic technology actually contributes to the improvement of communication contexts for people who are visually impaired. Even though human beings take advantage of their five sensory channels (i.e., sight, sound, taste, smell, and touch) to interact with their environment, the sense of touch is the only sense that enables people to modify and manipulate things in the world (Minogue & Jones, 2006). Furthermore, the touch sensation is superior to vision in terms of the perception of certain properties (e.g., textures, compliance, elasticity, viscosity) (Minogue et al., 2006). People with visual impairment are often adept at tactile processes, and they attempt to interact with their environment through the sense of touch. According to brain plasticity theory, human beings have the capability to compensate for their handicaps through the reorganization of brain structure, which often results in enhanced capabilities in the remaining modalities, such as haptic perception. The sensory modality of touch in people with visual impairment becomes more enhanced than it is in sighted people. The use of this enhanced sensory channel, touch, can contribute to their communication context. Generally, haptic technology is developed by focusing on the sense of touch to assist people with visual impairment to obtain rich information and survive in a world despite visual impairment.

Older adults with low vision can also be a target user group for haptic technology. Older adults' everyday lives are considerably influenced by haptics (Baccini et al., 2006; Virginia Assistive Technology System, 2004). The sense of touch contributes to a variety of perceptual functions, such as (a) assessments of an object's dynamic and material properties (e.g., texture and weight), (b) verification of engagement and completion (e.g. automobile gear shifting), (c) continuous monitoring of ongoing activity and gradual change (e.g., pencil sharpener), (d) building mental models for invisible parts of a system (e.g., recognition in the darkness), and (e) making judgments of other people (e.g., a handshake) (MacLean, 2000). Examples of haptic technology applications for the elderly include an omni-directional mobile wheelchair with a haptic joystick (Urbano, Terashim, Miyosh, & Kitagawa, 2005), an intelligent walker with a haptic handle bar (Shim, Lee, Shim, Lee, & Hong, 2005), and vibrating insoles for balance improvement (Priplata, Niemi, Harry, Lipsitz, & Collins, 2009).

1.2. Research problem

However, a great number of users are dissatisfied with their assistive technology applications. Unfortunately, such dissatisfaction is likely to cause abandonment of the technology devices. For example, a national survey on technology abandonment reported that almost one-third (29.3%) of all devices previously used were completely abandoned (Phillips & Zhao, 1993). The abandonment of assistive technology is still of great interest to today's researchers (Hoppestad, 2007; Riemer-Reiss, 2000; Riemer-Reiss & Wacker, 2000). In particular, a recent study reported that the adoption rate of haptic technology is low (Bjelland & Tangeland, 2007). Unfortunately, the discontinuance of the use of assistive technology devices results in a waste of time, money, freedom, and loss of function in individuals with disabilities (Phillips et al., 1993; Riemer-Reiss, 2000). Factors that cause abandonment include lack of user opinion in developing the device, poor device performance, and changes in user needs (Phillips et al., 1993). Rogers (1995) identified five fundamental attributes that contribute to a user's decision to adopt new technology and concepts: compatibility, relative advantage, complexity, triability, and observability. If an assistive technology application does not comply with those attributes, a user's decision is likely to result in abandonment. Of all the factors that lead to abandonment, the most significant is the failure to meet user needs (Riemer-Reiss, 1999) as feedback from an intended user with disabilities indicates: "Talk to the user. Be a little more considerate of the end-user. Don't assume anything. Ask the consumer. Listen to me! I know what works for me" (Phillips et al., 1993, p. 42). Thus, doubts have been raised about existing design approaches in assistive technology application development, revealing a great need to explore whether existing design approaches properly reflect assistive technology user needs, especially for haptic technology.

Today, Nielsen's usability engineering model is widely used in the Human-Computer Interaction (HCI) domain (Nielsen, 1992). The model consists of three phases of software development or user interface design: (a) pre-design, (b) design, and (c) post-design. The first stage, pre-design, is focused on understanding target users and tasks they perform. The second phase aims to develop a prototype that meets established usability principles and to conduct a validation study with intended users. After the second phase, a product is released. The primary objective of the third phase, post-design, is to collect data for the next version of the product and new future products. Because this present research focused on whether the needs of users with disabilities were correctly reflected in the product, it partially covered Nielsen's usability engineering model; in other words, target users and user needs were solicited, but a validation procedure was not included in this research.

1.2.1. Target users in the same disability category and accessibility

Little attention has been paid to different needs of users who fall into the same disability category, although there is no doubt that numerous HCI researchers and practitioners have attempted to enhance accessibility over the past 20 years (Keates, Clarkson, & Robinson, 2002). In the U.S., the barrier-free design approach emerged during the civil rights and disability rights movements to protect people with disabilities from discrimination (Keates, Clarkson, Harrison, & Robinson, 2000; Keates et al., 2002). Barrier-free design approaches led to the development of Section 504 of the Rehabilitation Act (US General Services Administration, 1973), Section 508 of the Workforce Investment Act (US General Services Administration, 1998), and the Americans with Disabilities Act or ADA (Kelly, 1995). In addition, a variety of design approaches emerged that facilitated accessibility, including "Rehabilitation Design," "Design by Story-Telling," "Transgenerational Design," "Universal Design," "User Pyramid Design Approach," and "Inclusive Design" (Keates et al., 2002; Newell & Gregor, 2000). Various regulations (e.g., Section 508) and design approaches contributed to the development of accessibility designs for users with special needs. However, a key question that should be addressed is whether the regulations and design approaches have considered the heterogeneous needs of users in the same disability category. In general, designers tend to assume that there are no individual differences among users having the same disability. In fact, most existing design approaches focus primarily on the different needs of users with and without disabilities (Douglas & Willson, 2007; Sjostrom, 2001a; Sjostrom et al., 2003). However, people in the same disability category often have very different views on specific issues (Luck, 2003). For instance, different performance outcomes are often observed in people with different degrees of vision loss (Blanco & Travieso, 2003; Jednorog & Grabowska, 2008; Plimmer, Crossan, Brewster, & Blagojevic, 2008). In addition, different types of interactions with a system have also been detected. In short, these groups of individuals with different degrees of vision loss performed the same task differently.

To gain a better understanding of the differences among people with various visual impairments, a fundamental issue must first be addressed: the mental model of those whose vision is impaired. The relevant theoretical and empirical literature has suggested that people with visual impairment rely on an indirect, top-down, and interpretive approach, which is consistent with Gregory's indirect perception theory (mental model).

People with visual impairment have mental models distinct from those of sighted people (Kurniawan & Sutcliffe, 2002; Kurniawan, Sutcliffe, Blenkhorn, & Shin, 2003). In addition, Millar (1994) contended that there are individual differences between people with visual impairment and sighted people in terms of how they code spatial information.

Carneiro and Velho (2004) pointed out that people with visual impairment rely on their remaining channels (e.g., long-term memory, auditory, and haptic) to understand the world. For instance, by using the sense of touch, they can facilitate their understanding of the world (e.g., objects' shapes, sizes, textures, and spatial positions). In general, mental models are constructed by visual trace and visuospatial mental images. While visual trace originates directly from vision (or a visual experience), a visuospatial mental image is generated based on other sources of information such as a haptic sensation, an auditory sensation or long-term memory (Cornoldi & Vecchi, 2000). Consequently, people with visual impairment are expected to take advantage of the visuospatial mental image to recognize objects because the sense of touch serves as a major channel for communicating with the world. Outputs induced by a visual trace (as in sighted people) and a visuospatial mental image (as in people with visual impairment) can be different because they are derived from different processing mechanisms (Cornoldi et al., 2000).

Many empirical studies observed that people with different vision conditions perform differently at the same task (Dulin, 2007). Those individuals' brains were investigated through brain-imaging technology such as functional Magnetic Resonance Imaging (fMRI), and it was uncovered that people with different degrees of visual impairment showed different degrees of brain plastic changes in the occipital and parietal cortices. Many researchers believe that the damaged visual sensory modality triggers the brain plastic changes, which typically result in enhanced capability in the remaining modalities (e.g., haptic perception). Based on the theory of brain plasticity, many neuroscience researchers have studied different brain activities and performance differences between sighted people and those with total blindness. However, very few of the prior studies considered those with low vision who are between these two extremes. Designers have viewed visual impairment as "all" or "nothing", and have not given attention to those with low vision who represent the majority of people with visual disabilities. It is expected, although those with residual vision do not lose all vision, brain plasticity would still occur to compensate for the loss of vision they do have, thereby influencing their haptic perception.

People with visual impairment interact with the world through indirect perception; that is, through a mental model (see Figure 2). The mental model is constructed by different information channels (e.g., a sense of touch). Given the brain plasticity theory that individuals with different vision conditions would have different haptic perceptions, people with intact vision, those with blindness, and those with residual vision are likely to receive different touch-related information inputs, which would ultimately influence their mental models differently.

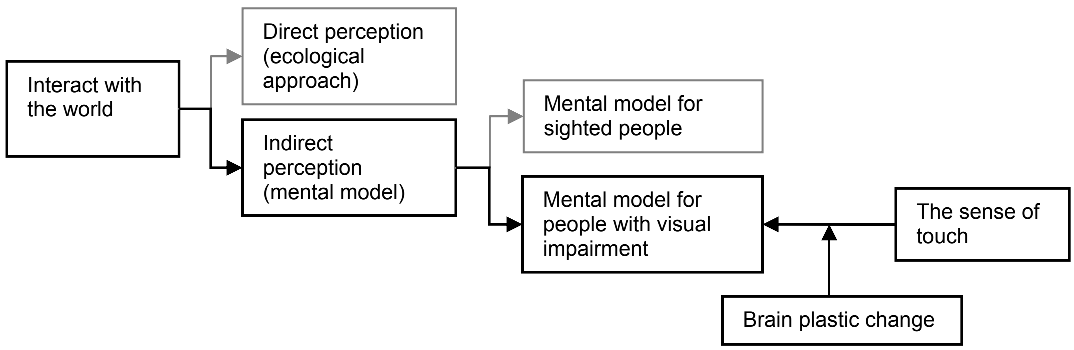


Figure 2. Mental model construction by those with residual vision influenced by brain plasticity

As shown in Figure 3, vision is also a route that facilitates mental model construction. People with total blindness cannot use the visual trace, but they can use the sense of touch that can be enhanced through brain plasticity. On the other hand, people with intact vision can use both a visual trace and a visuospatial mental image, but their sense of touch will not be enhanced as much as those with visual impairment. Finally, those with residual vision can use both a visual trace and a visuospatial mental image. In addition, those with residual vision can take advantage of the sense of touch, which is somewhat enhanced by brain plasticity, as well as still rely on their somewhat impaired vision. Therefore, their mental models would be influenced by both routes (i.e., a visuospatial mental image and a visual trace) in a way different from those who are blind and those with intact vision. Taken together, people with residual vision might perform differently based on haptic capability and behavior (interaction with the world) compared to those who are blind or those with intact vision (see Figure 4). Psychophysical scaling techniques could be used to measure capability in the haptic modality. Interactions with haptic user interfaces can be investigated by a design method in a usability study domain.

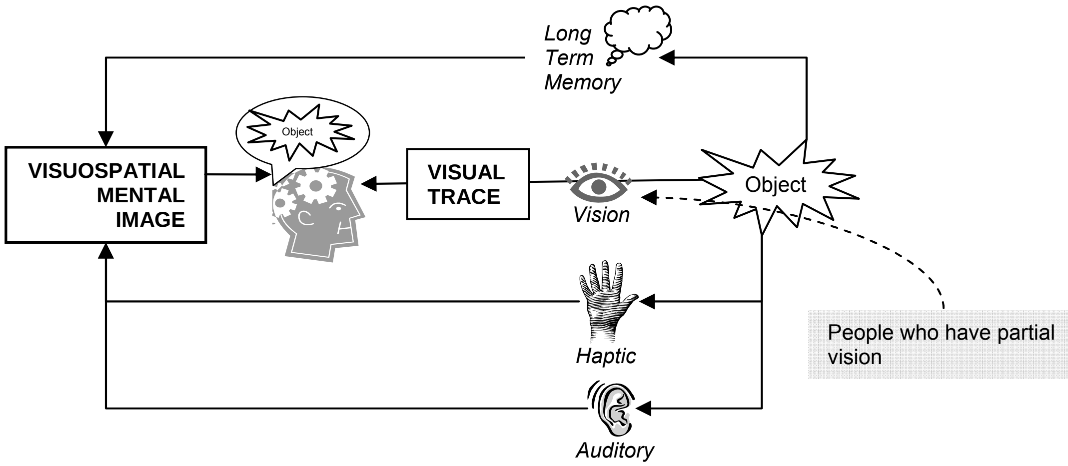


Figure 3. People with partial vision still rely on the visual modality in addition to the other modalities

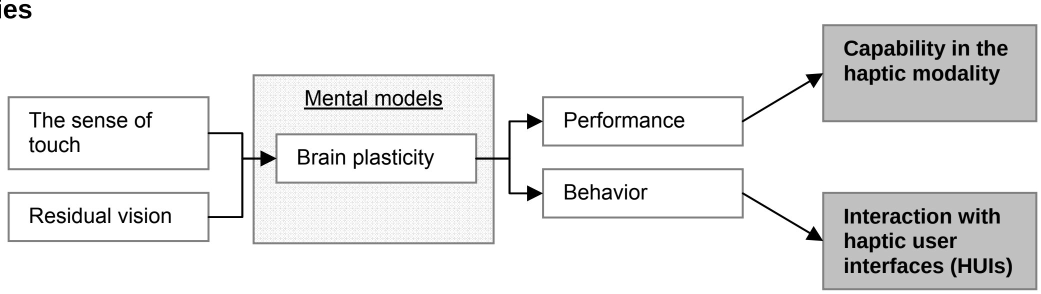


Figure 4. Two primary themes (i.e., capability in the haptic modality and preferences for HUIs) in this research

To measure the extent to which the sense of touch in those who have residual vision is enhanced, a magnitude estimation technique can be used. A magnitude estimation technique is typically facilitated by psychophysical scales of sensation. Steven's power law is useful in psychophysics because it can scale almost any sensory dimension (Schiffman, 2000). Therefore, the magnitude estimation based on Steven's power law can be applied to this research as an ideal psychophysical scaling technique that contributes to the calculation of how much of a given objective stimuli an individual subjectively perceives. Analysis of human's haptic perception is generally conducted by a physical measurement of roughness (Tiest & Kappers, 2006). The roughness measurement is quite often facilitated by using sandpaper stimuli (Bergmann Tiest & Kappers, 2006d; Bergmann Tiest & Kappers, 2007; Diamond & Lawless, 2001; Suzuki, Gyoba, & Sakamoto, 2008; Verrillo, Bolanowski, & McGlone, 1999).

1.2.2. User needs elicitation method

Besides capability in the haptic modality, interaction with haptic user interfaces is also influenced by mental models and brain plasticity. Because people have different haptic capabilities, it is postulated that they deal with haptic interfaces differently and require different user interface designs. Therefore, a user needs assessment is needed in order to explore how people deal with haptic user interfaces differently. However, to investigate how they interact differently with haptic user interfaces and what types of interfaces they want, we first should investigate whether today's design approaches are applicable to such design contexts as users with visual impairment and nongraphical user interfaces. The following is a quick review of today's design approaches with regard to HUI designs and groups of users who have disabilities, particularly visual impairment. A comprehensive review is offered in the literature review section.

In existing design contexts, users with disabilities are less likely to become deeply involved in design developments. Furthermore, even some prior studies that included users with disabilities in design development merely focused on a summative evaluation and used blindfolded sighted participants. In this regard, the participatory design approach can contribute to user involvement throughout the design development process. The participatory design assigns users as codesigners and also empowers them to become deeply involved in the design development process (Buhler, 2001; Coleman & Sumner, 2004; Lindgaard & Caple, 2001).

Participatory design focuses on accomplishing design *with users' input*. Participatory design supports the notions that each individual has valuable ideas to contribute to the design and that users should be allowed to participate in design processes by expressing their needs directly. Varieties of design approaches in the participatory design have been formed. The approaches include an ethnographic field method (Blomberg, 1993), cooperative design (Bodker, Gronbaek, & Kyung, 1993), contextual design (Beyer & Holtzblatt, 1998), and PICTIVE (Muller, 1991; Muller, 1993). Although these four design approaches fall under the same participatory design umbrella, they are slightly different in terms of the prototyping technique, user involvement in the development of initial prototypes, partnership (or user empowerment), time, number of participants, purpose of the prototypes, communication, and identification of users' goals. Although each design approach has strengths and weaknesses, PICTIVE is more suitable for the purposes of this research. In the following sections, PICTIVE is further explored to determine its applicability to design contexts in this research, such as for nongraphical user interfaces (i.e., haptic user interfaces) with users who have visual impairment.

Designing haptic user interfaces has two design challenges. First, developing a comprehensive understanding of haptic technology is difficult. Second, there is a lower probability that users will take an independent position on a problem. According to Kensing and Blomberg (1998), ideally, a participatory design approach should facilitate users' involvement in a design decision-making process and provide users with an opportunity to take an independent position on an argument related to design solutions. PICTIVE is consistent with this guidance. Because simple office supplies are used in PICTIVE, it is easier for users to understand the prototypes and project the features of future target systems. In consequence, users' active participation is expected in decision-making processes associated with interface designs. In addition, users no longer rely on designers and remain independent with regard to design problems. PICTIVE is an ideal candidate to accomplish the participatory design of haptic technology successfully.

However, there remains some doubt as to whether PICTIVE is valid for users who are visually impaired. PICTIVE was originally designed to help sighted people demonstrate what they want to see in a future system (Muller, 1993). Participants who are visually impaired cannot take advantage of such prototyping techniques. Whereas designers are able to see a prototype (e.g., colored artifacts), users who are visually impaired are unable to do so. It is ironic that unequal accessibility issues occur during the design of assistive technology applications for people with disabilities. The prototyping technique of PICTIVE must be modified to allow participants with visual impairment access to relevant information about design developments.

As discussed earlier, people with visual impairment primarily depend on other channels, such as touch and auditory sensations and long-term memory, when constructing mental models of the world. It is apparent that all the remaining modalities contribute to cognitive efforts. However, of these modalities, the sense of touch is primarily engaged in the cognitive efforts of people with visual impairment. Furthermore, brain plasticity theory suggests that people who are visually impaired typically have enhanced capabilities in touch modality. Therefore, the sense of touch is considered an ideal way to interact with the world. A touch-based PICTIVE design activity could be developed by considering several theories such as haptic exploratory procedures (Lederman & Klatzky, 2004; Lederman & Klatzky, 1987) and spatial coding (Millar, 1994).

Lederman and Klatzky (1987) modeled the pattern of hand movements in exploring objects, called haptic exploratory procedures. Lederman and Klatzky's model supports that people with visual impairment are able to perceive *material properties* by touch. By considering their model, various material properties (e.g., texture, hardness, and shape) can be assigned to prototyping artifacts so that participants with visual impairment can distinguish prototyping artifacts by touch. Furthermore, they can assign specific meanings to each material property of given prototyping artifacts as the original PICTIVE technique assigns specific meanings to each color of prototyping artifacts (e.g., office supplies). Such material properties, for instance, can also be used as haptic user interface components (e.g., drop-down boxes, menu bars, and other icons) just as participants in the original PICTIVE technique designed graphical user interface components by using colored office supplies. Lederman and Klatzky's model can be applied to a prototyping artifact that is fixed at one location without any consideration of its movements and its relations with other prototyping artifacts.

Hatwell et al. (2003) contended that the sense of touch plays a critical role in perceiving the *spatial properties* (e.g., localization, length, line, and orientation) of stimuli in the real world. A reference frame is often used to enable one to localize a stimulus in the environment with respect to oneself (i.e., self-referent frame) or external points (i.e., external frame), called spatial coding (Millar, 1994). Millar (1994) recommended that the convergence of "body-centered kinaesthetic" and "proprioceptive" information presents a reliable method of spatial coding in haptic conditions. The primary contribution of kinaesthetic information coming from a body or a body part would serve as a location anchor for starting or stopping a movement. A body or a body part could also be used as a coordinate reference frame to identify the location of an object. When an object's initial position is changed or an observer is replaced, movement sequences are coded (Millar, 1994). To facilitate movement coding, additional cues or frames should be provided for use as a reference. Thus, users who are visually impaired could be provided with a cardboard box (i.e., a 3-dimensional cube with x, y, and z axes) as an additional cue or frame. Within the space inside the box, they could easily identify the positions of their body and prototyping artifacts. The box should be located just in front of the user's body. The sense of touch is integrated into the design activity of PICTIVE. This means that those visually impaired engage in designing nonvisual interfaces (e.g., haptic interfaces) through nonvisual communication methods (e.g., the sense of touch). This method could be called, “what you feel is what you get” (WYFIWYG) because content tangibly presented during design developments will be very similar to that in the final outcome.

1.3. Significance of the study

This research can contribute to *usable accessibility*. A considerable amount of prior research has been focused on *accessibility* for users with disabilities, but not *usability*. Today, many users are dissatisfied with assistive technology. In addition, most previous studies paid attention only to individual differences between people *with and without* disabilities. Very few previous studies considered heterogeneous user needs for people in the same category of disability. For instance, most prior studies were less concerned about users with low vision than users with total blindness. In addition, older users with low vision were less likely to be included in haptic user interface design processes as compared to their younger counterparts. Although there are almost three times as many people with low vision than with total blindness (Jacko et al., 2003) and low vision is more common among older adults (Center for Persons with Disabilities, 2008), little attention has been paid to the needs of the elderly with low vision, especially in regards to haptic technology designs. This research took into account low vision (in a vision-related individual difference study) and aging (in an age-related individual difference study). In addition, this research noted that conventional design methods were inapplicable to new design contexts, such as users with visual impairment using nongraphical user interfaces. In contrast to previous studies in the HCI domain, this research took a different approach to understand individual differences and develop a design method. Cognitive neuroscience was employed to explore these heterogeneous needs related to haptic user interfaces. More specifically, users’ brain activity, brain functional changes, enhanced capability in the haptic modality, users’ behavior and performance were all taken into account. A new design tool – a touch-based prototyping technique – was also developed based on brain plasticity. The aforementioned significance of this research is summarized below:

- The present research can contribute to an understanding of the individual differences among users with “low vision” and intact sight in terms of physiological heterogeneity (i.e., capability in the haptic modality) and heterogeneous haptic user interface needs.
- The present research can contribute to an understanding of individual differences among younger and “older users” with low vision in terms of physiological heterogeneity (i.e., capability in the haptic modality) and heterogeneous haptic user interface needs.
- The present research used a new approach in understanding individual differences among users with visual impairment, and developing a more accessible participatory design process for those with visual impairment.
    - It involves a combination of theoretical perspectives in neuroscience (e.g., brain plasticity) and psychology (e.g., mental models).

Improving the usability of a target system for those with special needs is a critical design issue. If those prospective users with special needs are dissatisfied, the affect does not just end with users’ frustration, but they will be more likely to abandon the unsatisfactory system and eventually fail to achieve independence in everyday life. In addition, their vocational opportunities and job security could also be negatively influenced. According to the U.S. Census Bureau (2003), the total number of people with disabilities age 16–64 is more than 33 million. Of these, only 18 million, or 55.8%, are employed. Many employers have reported that providing proper accommodations (e.g., assistive technology) for employees with disabilities has resulted in multiple benefits, enabling their company to retain a qualified employee, eliminate the costs of training a new employee, and increase the worker’s productivity (Hendricks, Batiste, & Hirsh, 2005).

Those with special needs should be given an equal opportunity to develop employable skills and obtain jobs. Properly designed assistive technology applications can contribute greatly toward this goal. In that regard, the present research aims to contribute to improving the usability of assistive technology for people with special needs.

1.4. Benefits of the study

This research will contribute to the usability and methodology domain by developing a more accessible participatory design process based on PICTIVE, and some of the accessibility features could also be applicable to other participatory design approaches. In addition to users with visual impairment, the modified PICTIVE design approach could be beneficial to researchers, professionals, and students with visual impairment in Human Factors (HF) and HCI areas.

Additionally, this research could motivate HF/HCI researchers to consider the applicability of other existing graphical user interface design methods to new design contexts. As technology advances, new types of user interfaces can be introduced, which will go beyond traditional graphical user interfaces. By considering the results of the present study, HF/HCI researchers could expand research by investigating whether other traditional design methods are applicable to the new types of user interfaces and users' disabilities.

While evaluating PICTIVE-based design methods, participants should produce a list of user needs, which can be used as a heuristic list. Given the list, a heuristic evaluator will be able to determine which usability aspects should be carefully explored.

As a long-term benefit, the user needs and the design method proposed in this research can ultimately contribute to a reduction in the abandonment rate for assistive technology applications, a result that would positively influence the capability of those with visual impairment to live independently, their job security, and manufacturers' profits. Using similar technologies, users with visual impairment can achieve the same benefits as those who have no apparent visual disability. Benefits of this research are summarized below:

- The development of user needs in haptic user interfaces (HUIs) with regard to individual differences by age and vision, which can be used as a set of HUI design guidelines.
- The development of a more accessible participatory design process for not only users with visual impairment, but also professionals, researchers, and students with visual impairment in HF and HCI areas.
- Application of some of the accessibility features of the modified PICTIVE design to other participatory design approaches.

- Motivation to investigate the applicability of other traditional design methods to nontraditional user interfaces and to users with disabilities.
- A usability testing instrument that integrates haptic user interface needs with a heuristic evaluation method, which will help to examine a haptic-embedded assistive technology application and improve its usability.
- Reduction in the abandonment rate for haptic assistive technology, ultimately enhancing the capability of those with visual impairment to live independently, their job security, and manufacturers' profits.

The need for advancing accessibility and usability is not just limited to helping people with disabilities. Many people, indeed, have problems with information technology (IT) but are afraid to admit it. Thus, research into offering people alternative ways of accessing technology eventually benefits everyone.

1.5. Research goals, questions, and approaches

This research primarily was designed to examine the heterogeneous attributes of users' capabilities in the haptic modality and user needs in haptic user interfaces. Research goals, questions, and approaches are described in detail below and are summarized in Figure 5 and Table 2.

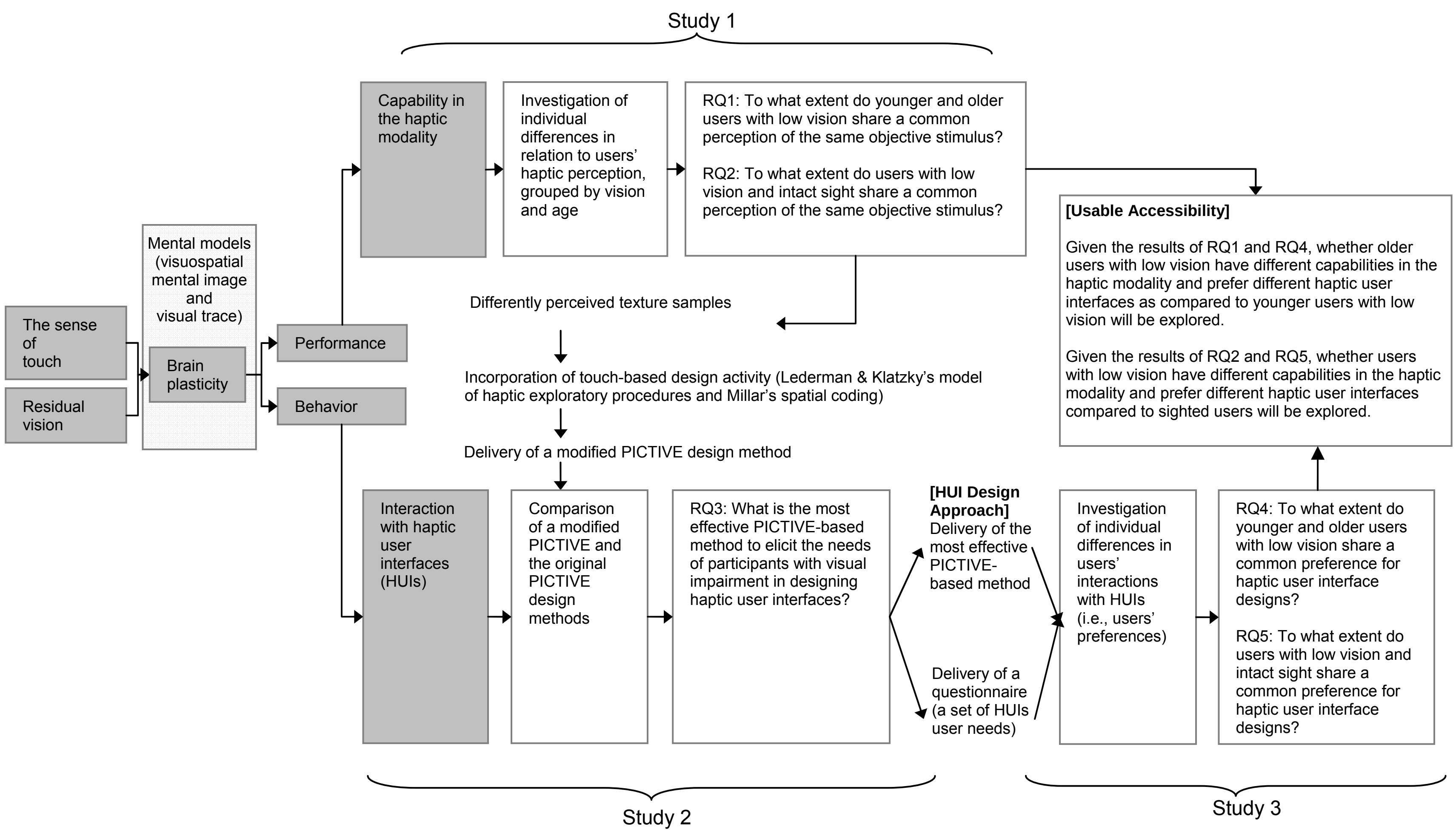


Figure 5. Conceptual model of this research

Study 1: Study 1 focused on the investigation of individual differences in users' capabilities in the haptic modality based on age (i.e., younger versus older) and visual disability (i.e., low vision versus intact vision). In general, in contrast with younger individuals with low vision, older individuals with low vision are more likely to experience age-related sensory degeneration, which would differently affect brain plasticity and mental models. Thus, the degree to which older users with low vision have enhanced capabilities in the haptic modality was expected to be different from their younger counterparts. As discussed previously, sighted users and users with low vision have different vision conditions, which would differentially influence brain plasticity and mental models (visuospatial mental image and visual trace). Users with low vision were anticipated to have enhanced capability in the haptic modality compared to sighted users.

To explore users' haptic capabilities, a magnitude estimation technique was used to investigate how differently each group of participants (classified by age and vision) perceived the same objective stimulus, such as haptic perception. The research questions below were explored:

Research Question 1: To what extent do younger and older users with low vision share a common perception of the same objective stimulus?

Research Question 2: To what extent do users with different vision statuses (i.e., low vision and intact vision) share a common perception of the same objective stimulus?

To explore user needs in haptic user interfaces, the elicitation method for user needs should accommodate participants with visual impairments who are engaged in haptic user interface design activities. Study 1 aimed to modify an existing participatory design approach (i.e., PICTIVE) by incorporating the sense of touch into the design process (e.g., the use of differently perceived texture samples among target users). Several theoretical perspectives on touch, representation and visual impairment were employed to modify the original PICTIVE method (e.g., Lederman and Klatzky's [1987] model of haptic exploratory procedure and Millar's [1994] spatial coding).

Study 2: The modified PICTIVE method developed in study 1 was evaluated by intended users who are visually impaired (e.g., low vision). Participants were randomly assigned into two groups, each of which used either the modified or the original PICTIVE method to design haptic user interfaces. In particular, the fundamental elements of haptic user interfaces proposed by Sjostrom (2001b) were designed, such as haptic interface navigation, finding objects, overview, understanding an object, and discrimination of objects. Later, participants were instructed to evaluate an assigned method by completing a questionnaire. This research sought to answer the following research question:

Research Question 3: What is the most effective PICTIVE-based method to elicit the needs of participants with visual impairment in designing haptic user interfaces?

In the research problem section, the need for a more accessible participatory design process was discussed. Study 2 contributed to enhanced accessibility of a participatory design method for participants with visual impairment, specifically PICTIVE. Indeed, another contribution was made to the development of a questionnaire that should be used in Study 3. In fact, when evaluating the design methods in Study 2, participants were asked to design the fundamental elements of haptic user interfaces. As a result, participants should produce a list of users' needs in haptic user interfaces.

Study 3: Individual differences in user needs for haptic user interfaces were examined in participants classified by age and vision. The questionnaire developed in Study 2 consisted of a set of haptic user interface design ideas. Participants were instructed to rate each design idea to show how much they agree with it. Participants were asked to complete the questionnaire individually. This research sought to answer the following research questions:

Research Question 4: To what extent do younger and older users with low vision share a common preference for haptic user interface designs?

Research Question 5: To what extent do users with different vision statuses (i.e., low vision and intact vision) share a common preference for haptic user interface designs?

Additional research was conducted to explore the relationship between RQ1 (Study 1) and RQ4 (Study 3) and between RQ2 (Study 1) and RQ5 (Study 3). Table 1 illustrates how the components of the four research questions are related.

Table 1. Components related to studies 1 and 3

	Age	Visual status
Capability in the haptic modality	Research Question 1	Research Question 2
Haptic user interface needs	Research Question 4	Research Question 5

The research problem discussion led to the anticipation that older users with low vision would have different capabilities in the haptic modality, which would eventually result in different haptic user interface needs compared to their younger counterparts. RQ1 addressed whether users from different age groups (i.e., younger versus older) with low vision have different capabilities in the haptic modality, and RQ4 addressed whether younger and older users with low vision prefer different haptic user interface needs. By considering the answers to RQ1 and RQ4, the question as to whether older users with low vision have different capabilities in the haptic modality and prefer different haptic user interfaces compared to younger users with low vision, was explored.

In the research problem section, usable accessibility issues, such as the rate of abandonment for assistive technology and the heterogeneous needs of users with visual impairment, were discussed. The discussion led to the postulate that users with low vision would have different capabilities in the haptic modality, which would in turn cause different haptic user interface needs compared to sighted users. RQ2 addressed whether users with different vision statuses have different capabilities in the haptic modality. RQ5 asked whether users with different vision statuses have different haptic user interface needs. By considering the results for RQ2 and RQ5, the question of whether users with low vision have different capabilities in the haptic modality and prefer different haptic user interfaces when compared to sighted users was explored.

Table 2. Research goals, questions, and approaches

	Research Goals	Research Questions	Research Approaches
Study 1	To examine individual differences in users' capabilities in the haptic modality among people grouped by vision and age	Aging: To what extent do younger and older users with residual vision share a common perception of the same objective stimulus? Visual impairment: To what extent do users with different vision statuses share a common perception of the same objective stimulus?	Magnitude estimation technique to measure the subjective perceptions of objective stimuli
Study 2	To explore the applicability of design approaches to certain design contexts, such as users with visual impairment and nongraphical user interfaces	What is the most effective way to elicit user needs for participants with visual impairment in designing haptic user interfaces?	Comparison of the modified PICTIVE with the original PICTIVE
Study 3	To examine individual differences in users' needs in haptic user interfaces among people grouped by vision and age	Aging: To what extent do younger and older users with low vision share a common preference for haptic user interface design? Visual impairment: To what extent do users with different visual impairment share a common preference for haptic user interface design?	Investigation of users' preferences for haptic user interfaces with regard to interface navigation, finding objects, overview, understanding an object, and discrimination of objects (Sjostorm, 2001b)

1.6. Document overview

The remainder of this document includes a literature review (Chapter 2); discussion of Study 1 (Chapter 3), Study 2 (Chapter 4), and Study 3 (Chapter 5); and a conclusion (Chapter 6). Chapter 2 primarily provides an overview of the characteristics of users with visual impairment, existing design approaches for users with disabilities, and relevant theoretical perspectives. Chapters 3, 4, and 5 focus on three studies (i.e., knowing target users' haptic perception, development of a more accessible design method, and understanding of haptic user interface needs), including experimental designs, independent variables, dependent variables, participants, equipment, procedures, data analyses, results, and discussions. Conclusions appear in Chapter 6, which contains a summary, contribution, implication, further consideration, and future research.

CHAPTER 2. LITERATURE REVIEW

2.1. Individuals with visual impairments (blindness and low vision)

Many previous studies did not validly use such terms as blindness, low vision, and visual impairment. The World Health Organization (WHO) found that 65 different definitions of blindness and low vision are currently used (Dunlea, 1989). In this research, the definitions described by the WHO (2008c) are used; these are also consistent with the view of the American Foundation for the Blind (AFB) and Individuals with Disabilities Education Act (IDEA) (Table 3). Visual acuity is typically used to decide whether an individual is classified as being blind or having low vision. For example, an individual whose visual acuity is 20/100 (in the better eye with the best possible correction, as measured by a Snellen vision chart) is able to see at 20 feet what an individual with 20/20 visual acuity sees at 100 feet. Blindness is defined as visual acuity worse than 20/400 in the better eye with the best possible correction. Low vision is defined as visual acuity of less than 20/70, but equal to or better than 20/400 in the better eye with the best possible correction. According to the WHO, visual impairment includes blindness, as well as low vision. The categorization of visual impairment currently in use worldwide is based on the International Classification of Diseases (ICD) 10th revision, which is derived from the WHO Study Group on the Prevention of Blindness (World Health Organization, 2008a). However, as indicated in Table 3, the WHO has recently replaced the term “low vision” with moderate visual impairment (category 1) and severe visual impairment (category 2).

Table 3. Classifications of visual impairment based on visual acuity

Category	Worse than:	Equal to or better than:
Mild or no visual impairment 0		20/70
Moderate visual impairment 1	20/70	20/200
Severe visual impairment 2	20/200	20/400
Blindness 3	20/400	20/1200
Blindness 4	20/1200	Light perception
Blindness 5	No light perception	

Note: In the better eye with the best possible correction, as measured by a Snellen vision chart.

One misconception is that the majority of those with visual impairments fall into the category of blindness; however, most of these individuals retain some residual vision and actually fall into category 2 (severe visual impairment) or category 1 (moderate visual impairment). Visual impairment (i.e., blindness, low vision) is one of the most feared disabilities and its impact on personal, economic, and social life is profound (West et al., 2001). There are approximately 45 million people with blindness worldwide, the population of which increase by 1-2 million each year (US National Institutes of Health, 2002; West et al., 2001). Every seven minutes, an individual in the United States becomes visually impaired or blinded (Mroczka, 2005). The AFB (2008) estimates that there are approximately 1.3 million people in the United States who are categorized as legally blind. Legal blindness was originally defined by law to determine eligibility for benefits. According to AFB (2008), legal blindness is referred to as the central acuity of 20/200 or less in the better eye with the best possible correction (as measured by a Snellen vision chart) or a visual field of 20 degrees or less. Legal blindness includes blindness and low vision (severe) by the definition of WHO. As seen in Figure 6, the population with legal blindness can be broken down into two categories: (1) those with some residual vision remaining (i.e., 80%), and (2) those with only light perception or less vision (i.e., 20%). Of those who only have light perception or less vision, 50% are individuals with total blindness. In other words, only one out of 10 individuals who are legally blind is totally blind, and the majority of these retain some residual vision.

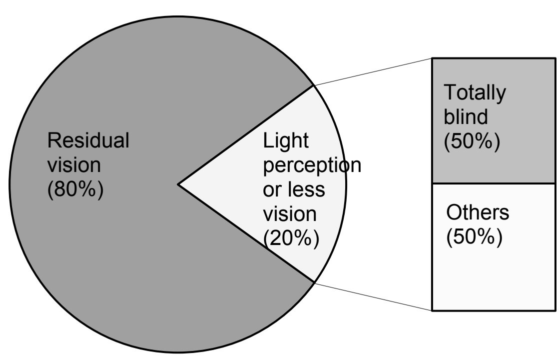


Figure 6. Breakdown of legal blindness by severity of vision loss

In a search of the literature, another misunderstanding about students with visual impairment was identified (i.e., blindness versus visual impairment). In general, in studies on students with visual impairment, researchers tend to look at special education programs, such as at schools for the blind. According to the latest report by AFB (2008), 93,600 students who have visual impairment are supported by special education programs in the United States. In fact, the population of students with visual impairment is most likely higher when public schools are included as well. According to The Virginia Department of Education (2005), 450 students with visual impairments in Virginia were educated in special education programs or public schools, and only 36 of these (i.e., 8%) were enrolled in special education programs (Figure 7). Many students with visual impairments study alongside sighted students in public schools.

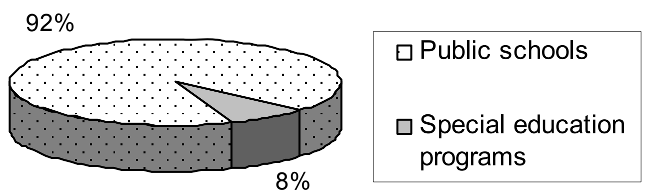


Figure 7. Of the 450 students with visual impairments in Virginia, 8% (36 students) are in special education schools and 92% (414 students) are in public schools

Unfortunately, Figure 7 also indicates that those students with special needs in public schools are more likely to encounter a lack of specially trained teachers who understand vision loss and its effects on education. It is not surprising that students with special needs rely primarily on assistive technology (AT) applications to survive in competitive educational environments. HCI researchers and practitioners should bear in mind that individuals with disabilities should have full access to the most appropriately designed AT devices so that they can have equal opportunities to obtain as much information as sighted individuals.

2.2. Challenges with existing assistive technology applications

However, there remains doubt as to whether AT devices can effectively carry visual information. Traditionally, Braille was the primary means to obtain information by students who were visually impaired (2008; Virginia Department of Education, 2005). However, today, only a small number of individuals with visual impairment are capable of reading Braille. For example, less than 10% of the visually impaired in the United States can read Braille (Petrie et al., 1997). Furthermore, a recent study (Fitzpatrick & Fitzpatrick, 2007) indicated that many young students who have visual impairment are not taught how to use Braille. Consequently, Braille may no longer be the primary means of obtaining information by those who are visually impaired.

Unfortunately, even students who are able to read Braille face challenges, especially in science classes. For instance, the disciplines of science, technology, engineering, and mathematics (STEM) generally incorporate numerous visually complex concepts related to waves, webs, shadows, cycles, color, and coils (Fitzpatrick et al., 2007; Karshmer & Gillan, 2003; Kumar & Ramasamy, 2001). However, Braille is based on low-tech displays such as paper and dots. Braille has limited capability to effectively represent such visually complex information (Aldrich et al., 1998; Karshmer et al., 2003; Yu et al., 2002; Yu et al., 2003). Presentation of a tactile graph also faces challenges in terms of the level of sensitivity, resolution, graph complexity, and array (Ebina et al., 1998). While people without visual impairment are able to distinguish two small, closely located dots via their visual sense, people with visual impairment hardly distinguish them. Some kinds of information are followed by complex numerical diagrams that generally contain numerous data points. A complex tactile figure is often difficult for people who have visual impairment to interpret. Additionally, multiple lines in graphs are often crossed, which is a challenge to trace by touch because there is a high likelihood of losing contact with one or more of the lines and becoming confused. Another challenge is that Braille consists of an array of three-by-two tactile dot matrices; thus, Braille text takes up much more space on paper than visual text. Given two pages of the same size, Braille transfers less information than visual text. This space issue is also likely to restrict the presentation of the coordinates of points plotted on a graph. A Braille graph must be larger than a vision-based one, making it difficult for people with visual impairment to get an overview of the entire graph.

Tactile diagrams are typically presented on paper, which causes several issues relevant to durability and hygiene. For example, raised dots are easily depressed or worn out after multiple usages (e.g., scrub). Furthermore, hygiene is of concern because so many people often use the same tactile material repeatedly, and thus, it becomes dirty (Yu et al., 2003).

The Internet offers great benefits to the visually impaired, who struggle to obtain information. However, a barrier remains in accessing graphically oriented presentation of information. Typically, screen-reading technology (e.g., JAWS, VoiceOver, and Dragon Naturally Speaking) is used to facilitate users’ understanding of the contents of Web pages. An auditory description cannot, however, effectively convey visual information to users who are visually impaired (Aldrich et al., 1998; Yu et al., 2002). The process of navigating Web pages is tedious due to linear output (Kuber, 2006). For example, the VoiceOver program scans words one-by-one and produces them audibly in sequence. Consequently getting an overview of the spatial layout of Web page components is difficult.

2.3. Haptic technology

Today, haptic technology has become an important component of effectively accessing information systems. A haptic device interacts with virtual reality interfaces in which users are allowed to manipulate and obtain mechanical feedback (e.g., vibration) from three-dimensional objects (e.g., images and graphs). The haptic interface is supported by a real-time display of a virtual environment where users explore by pushing, pulling, feeling, and manipulating the virtual objects with a device (e.g., a mouse or stylus). Users are able to experience simulations of various characteristics of the objects and the environment, such as mass, hardness, texture, and gravitational fields.

Haptic user interfaces are relatively new, but have been actively applied to the domain of human-computer interaction in virtual environments since the early 1990s (Kortum, 2008). Haptic technology is widely used across a variety of domains, including medical, automotive, mobile phone, entertainment, controls, education, training, rehabilitation, assistive technology, and the scientific study of touch (Hayward et al., 2004; Kortum, 2008). For example, Immersion Corporation, a company recognized worldwide for developing, licensing, and marketing haptic technology, reported that 2,000 medical simulators with haptic technology have been sold worldwide to hospitals and teaching institutions to train clinicians (Immersion, 2008). Haptic technology is also embedded in mobile phones to enhance users' communication experience related to ringtones, games, messaging, alerts, dialing cues, and user interfaces for touch screen presses. It was announced that as of September, 2008, over 25 million mobile phones featuring haptic technology were sold worldwide, 7 million in the second quarter of 2008 alone (Ayala, 2008). The use of haptic mobile phones had more than doubled compared with the previous quarter. Computerworld, an information technology magazine forming a U.S.-based hub of the world's largest global IT media network, currently includes haptic technology as one of the top 10 trends in personal technology (Elgan, 2007). Besides the industry domain, research on haptic technology is also rapidly growing, especially multidisciplinary studies, including in robotics, experimental psychology, biology, computer science, and system controls (Hayward et al., 2004). For instance, approximately 200 articles have been published that address the importance of haptic technology in the past few years alone (Reiner, 1999). In short, haptic technology is comprehensively used across various domains to improve communication environments, and is becoming common in people's everyday lives.

How does the human body interact with haptic sense? The term "haptic" commonly refers to the sense of touch. More specifically, the haptic sense consists of cutaneous touch and kinesthetic touch (Kortum, 2008; Sallnas et al., 2000; Sjostrom et al., 2003; Smith, 1997). Cutaneous touch is related to the sensations felt on surface features and tactile perception, which is conveyed via the skin. On the other hand, kinesthetic touch is part of the haptic sensations that involve muscles and tendons, which enable people to recognize the movements of limbs.

More precisely, the sensation of touch occurs when a person's skin is exposed to mechanical, thermal, or chemical stimuli (Cholewiak & Collins, 1991). Touch receptors are associated with various modalities: mechanical pressure or distortion (mechanoreception), heat and cold (thermoreception), and pain (nociception) (Schmidt, 1977). Mechanoreception is primarily related to haptic devices, so thermal and pain properties are not discussed in this research. Mechanoreception responds to sensations such as pressure, vibration, and tickle (see Figure 8). The sensory receptors relevant to mechanoreception are distributed over the entire body. There are five types of receptors: nerve endings, Meissner's corpuscles, Merkel's disks, Pacinian corpuscles, Ruffini endings, and hairy skin including follicle receptors. These receptors respond differently to stimuli. For example, Merkel's disks generate a long, irregular discharge rate that responds to forces on the skin; however, Ruffini endings generate a regular discharge. Human perception of mechanical pressure or distortion is influenced by a combination of responses to these different receptors (Kortum, 2008). These responses or messages from cutaneous receptors are ultimately transmitted to a region in each hemisphere of the brain called the somatosensory cortex (Schiffman, 2000).

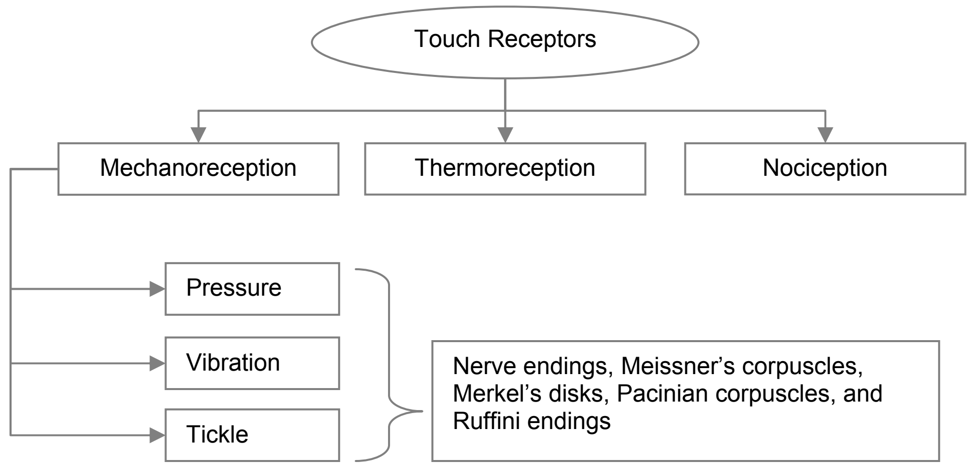


Figure 8. Three modalities related to touch receptors

Although all of these receptors contribute to the mediation of touch simulation, the Pacinian corpuscle is regarded as a distinctive receptor (Schiffman, 2000). Pacinian corpuscles are widely spread, but are located in the subcutaneous tissue of the skin. They are sensitive to pressure; thus, they can effectively sense a location or certain textural characteristics of a brief stimulus (Schiffman, 2000). In fact, the sensitivity involved in recognizing a location or textural characteristics varies depending on an individual's threshold for touch, which can be broken down into three types: absolute threshold, point localization threshold, and two-point threshold. Clearly, designers of haptic technology are encouraged to take into account the thresholds of intended users. Ideally, people can feel pressure when their skin is displaced less than 0.001 mm, but sensitivity varies from one region of the body to another (Schiffman, 2000). Schiffman (2000) reported data with regard to the three different thresholds. To assess absolute threshold levels, fine nylon filaments are normally used. The most interesting result is that the finger is one of the most sensitive parts of the human body. When it comes to localize touch sensations on one's skin, a specific body part such as a fingertip is extremely well localized (threshold = less than 2 mm) rather than the upper arm, thigh, or back (threshold = more than 10 mm). This explains why most haptic technology applications are designed to be operated by a pen-like stylus, which users hold with their fingers.

When hands are involved in exploring an object, especially by grasping and manipulating it, information from touch receptors correspond with other information called kinesthesis. Kinesthesis is related to the perception of body part position and movement stimulated by one's joints, muscles, and tendons (Schiffman, 2000). Pacinian corpuscles interact with one's joint movement. The sense of haptic is influenced by both the cutaneous touch and the kinesthesis touch.

2.4. Brain plasticity theory

Does such haptic technology contribute to the improvement of communication contexts for people who are visually impaired? There are considerable empirical findings indicating that losing a particular sensory modality leads to enhanced sensitivity in the remaining modalities. For instance, people who become deaf often have better vision (Neville & Bavelier, 2000). Individuals with hearing impairments performed faster and better compared to individuals without auditory impairment on a test in which they were asked to detect the direction of motion of a peripheral target (Neville & Lawson, 1987). Amputation of a finger or limb also leads to enhanced sensitivity in the remaining modalities (Millar, 2005). In addition, it was observed that people with visual impairment often showed enhanced sensitivity in their haptic modality (Jednorog et al., 2008). For instance, those with visual impairments had superior performance in tactile discrimination tasks (Grouios, Alevriadou, & Koidou, 2001). The use of their enhanced sense of touch can facilitate their communication contexts. Even though human beings take advantage of all five of their sensory channels (i.e., sight, sound, taste, smell, and touch) to interact with their environments, the sense of touch is the only one that enables people to modify and manipulate things in the world (Minogue et al., 2006). The sense of haptic is superior to vision in the perception of certain properties (e.g., textures, compliance, elasticity, viscosity) (Minogue et al., 2006).

According to brain plasticity theory, human beings have the capability to compensate for their handicaps by reorganizing the structure of the brain, which often results to enhanced capabilities in the remaining modalities, such as haptic perceptions in people who are visually impaired. The term 'plasticity' is originally derived from the Greek word "plastikos," which mean "to form" (Mundkur, 2005). Research in neuroscience and psychology lead to the invariable conclusion that brain plasticity (or often called cortical plasticity, neuroplasticity, or cortical remapping) serves the brain by changing its structure and function to compensate for damage and restore abilities (Kadosh & Walsh, 2006; Kolb & Whishaw, 1998). The brain also changes in response to training and experiences (Mundkur, 2005). The brain changes throughout one's entire life (Mundkur, 2005). The sense of touch becomes a critical channel through which information and interactions with the environments are obtained. Yu et al. (2003) empirically evaluated the effectiveness of haptic devices (e.g., PHANToM or Logitech WingMan Force Feedback mouse) for those visually impaired in accessing graphs and tables. Their experimental results indicated that a system that included haptic technology had advantages over traditional information-representation methods such as tactile diagrams. For example, using a tactile-diagram for a specific task, individuals with blindness, on average, got 87% of the questions correct, whereas in a haptic-embedded system, they got 96% of the questions correct. Additionally, such a significant difference between performances in the two systems was also observed in an accuracy test. The accuracy of information extracted from the tactile-diagram was 61.76%, whereas the accuracy increased to 85.88% in the haptic-embedded system.

Brain plasticity was furthermore investigated from an anatomical point of view to understand how vision loss and brain plastic changes contribute to an enhanced haptic sensory modality. First, the human brain is composed of four main parts, which include the frontal, parietal, temporal, and occipital lobes. Each lobe serves specific functions as seen in Figure 9 and listed in Table 4 (Hannan, 2006). For example, the parietal lobe contributes to the integration of sensory information from various senses such as spatial and visual information to facilitate motion and navigation. In addition, the parietal lobe is related to somatosensory perception, haptic, and reading. On the other hand, the occipital lobe plays a critical role in visual processing, visual perception, and reading capabilities associated with visual processing.

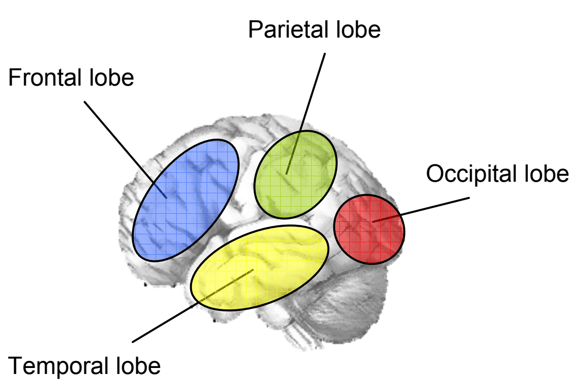


Figure 9. Lobes of the brain

Table 4. Functions of the lobes of the human brain

(Deleted due to copyright. Please, see Hannan, 2006, p. 398)

What is the mechanism whereby visual information is processed in the brain of sighted people? If an individual has sight, visual signals through retina should be engaged with the visual cortex to convert it into meaningful information. More specifically, visual information from the retina is first transmitted to a lateral geniculate nucleus (LGN) located in the central nerve system. The LGN sends projections to the primary visual cortex (V1). As illustrated in Figure 10, the V1 delivers information to two primary pathways, called the dorsal stream and the ventral stream (Goodale & Milner, 1992).

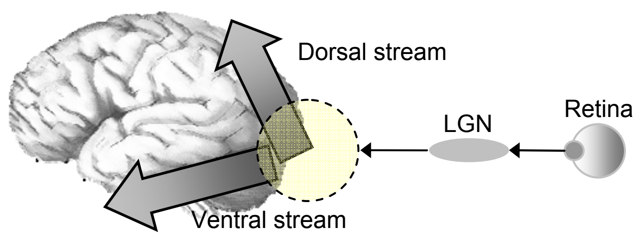


Figure 10. Pathways for visual information mapped onto the human brain

- Dorsal stream (V1→V2→V6→V5→posterior parietal cortex): The dorsal stream begins with V1 and goes through a visual area, V2, which is the second major area in the visual cortex, also called the prestriate cortex. The stream continues flowing to V6 (dorsomedial area), V5 (visual area MT), and the posterior parietal cortex. The dorsal stream is often called the “Where Pathway,” which primarily enables an individual to deal with the representation of objects’ locations, motions, and control of the eyes and arms.
- Ventral stream (V1→V2→V4→inferior temporal cortex): On the other hand, the ventral stream follows a different pathway after the visual area, V2. Instead, it goes through V4 and to the inferior temporal cortex. The ventral stream, often called the “What Pathway,” deals with object representation, form recognition, and long-term memory storage.

However, when sighted people are involved in tactile processes, such as reading Braille, their visual cortices are not used (Azari & Seitz, 2000). Surprisingly, people with early onset-blindness have an altered brain and use parts of the visual cortices in reading Braille or performing tactile discrimination tasks (Azari et al., 2000). There are numerous functional imaging studies of the brain that have employed functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), which are used to detect the functional activity of the visual areas in performing cognitive tasks in people with early-onset blindness (Lambert, Sampaio, Mauss, & Scheiber, 2004). These studies claim that activated visual areas are extrastriate visual areas. The extrastriate visual areas are located in a region of the occipital cortex and next to the striate visual area, which is also located in a region of the occipital cortex. A Brodmann area is often used to indicate the location of a particular cortex. According to the index system of Brodmann areas, the extrastriate cortex is composed of Brodmann areas (BA) 18 and 19. The striate cortex (also called V1, primary visual cortex) is placed at BA 17 (see Figure 11). Additionally, it was empirically demonstrated that BA 17, BA 18, and BA 19 were activated in people with blindness when they performed tactile tasks, whereas these areas were deactivated in sighted people performing the same tasks (Sadato et al., 1996).

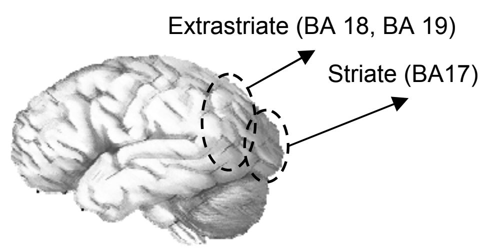


Figure 11. The occipital cortex includes the striate cortex (BA 17) and the extrastriate cortex (BA 18, BA 19)

Furthermore, activated visual areas in the occipital cortex (BA 17, 18, and 19) were closely associated with activity in the parietal cortex (e.g., somatosensory system) when people who are visually impaired are performing a tactile task. The somatosensory cortex is a distributed system in which information relevant to one’s own body is processed (Chen et al., 2008). The distributed system is composed of a primary (SI) and a secondary (SII) somatosensory cortex. The sense of touch is mainly processed in the SI. A homunculus is often used to describe the somatosensory cortex’s functions related to several parts of the body, such as the foot, hip, trunk, arm, hand, face, tongue, and larynx. As shown in Figure 12, a large area of the homunculus is assigned to the hands, which means that the function of the somatosensory cortex is to primarily receive and handle a lot of information from the hands.

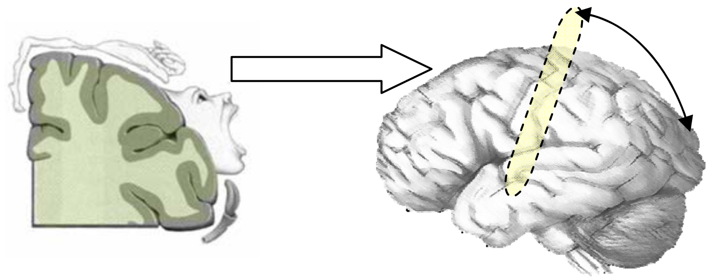


Figure 12. Sensory homunculus of the somatosensory cortex (left) and transferred information from the somatosensory cortex into the visual cortex (right) [public domain]

Although auditory cues contribute somewhat to information processing in people with visual impairment, the sense of touch plays a crucial role in interacting with the environment. Sadato et al. (1996) measured brain activity by using PET to determine whether the visual cortex received input from the somatosensory cortex during tactile discrimination tasks in sighted people and those with early-onset blindness. The results of Sadato's study (1996) indicated that input from the somatosensory cortex could be transferred to the primary visual cortex (V1) when people with blindness read Braille or performed other relevant tactile tasks. These results supported the notion that people who are visually impaired can alter and reorganize the brain to accept non-visual, sensorimotor information during tactile discrimination tasks. Such an increased connectivity between the occipital and parietal cortices is quite often observed in individuals with visual impairment (Burton et al., 2002). Typically, the increased connectivity results in enhanced abilities in the remaining modalities, such as the haptic modality (Jednorog et al., 2008). In short, haptic technology facilitated by the sense of touch can serve as a critical component of information processing in people with visual impairment in interacting with the world. In fact, Reiner (1999) discussed the benefits of the sense of touch in interacting with the environment. Specifically, Reiner presented "embodied experiences" in which tacit embodied knowledge is linked to objects and bodily activities. He stated that haptic user interfaces contribute to promoting the use of bodily, non-propositional knowledge, which in turn leads to the building of more accurate mental models and representations of the environment.

2.5. Today's haptic technology implementations

Numerous researchers have tried to apply haptic technology to help those visually impaired to understand graphic-based concepts (Brewster, 2002; Liffick, 2003; Plimmer et al., 2008; Sjostrom et al., 2003). For example, Plimmer et al. (2008) studied the haptic-based educational software called McSig. Educators of students with visual impairment reported that McSig was helpful to students in understanding geometric principles. The Moose project (Liffick, 2003) devised a force-feedback mouse to represent graphical interfaces such as windows, icons, and checkboxes, as well as spatial maps, to help students with blindness understand line graphs. In addition to the educational field, a variety of domains have taken advantage of haptic technology for the benefit of individuals with visual impairment. Many information technology professionals and researchers have devised haptic-embedded applications including, for example, a haptic-embedded Internet browser (Roth, Petrucci, Assimacopoulos, & Pun, 2000b), games (Roth, Petrucci, Assimacopoulos, & Pun, 2000a), maps (Harder & Michel, 2002; Lahav & Mioduser, 2008), a handheld device (Hoggan, Brewster, & Johnston, 2008), and E-trade (Proctor & Vu, 2005). For instance, Carneiro and Velho (2004) empirically explored the use of touch-based interfaces by individuals who had visual impairment. They observed that participants' error ratio was significantly reduced and their performances were enhanced, as well. Haptic-based assistive technology systems can be considered a potential way to enhance communication contexts for people with visual impairment.

Of the many haptic applications, PHANToM™ is the most commonly used haptic device (Kortum, 2008; Nikolakis, Tzovaras, Moustakidis, & Strintzis, 2004). PHANToM™ is typically operated with a pen-like stylus that permits simulation of the fingertip in contact with certain objects in virtual environments (see Figure 13). When a user, for instance, moves the pen-like stylus (synchronized with a virtual point-probe in three-dimensional virtual environments), the virtual point-probe of PHANToM™ follows the x, y, and z coordinates. When it touches a virtual object, relevant mechanical stimulations are delivered back to the pen-like stylus that the user holds. While traditional GUIs rely on visual cues such as unidirectional interaction with users, haptic user interfaces use mechanical signals as a bidirectional interaction with users (Carneiro & Velho, 2004). The presence of multiple cues and feedback can facilitate understanding of individuals with visual impairment in regards to graphic information.

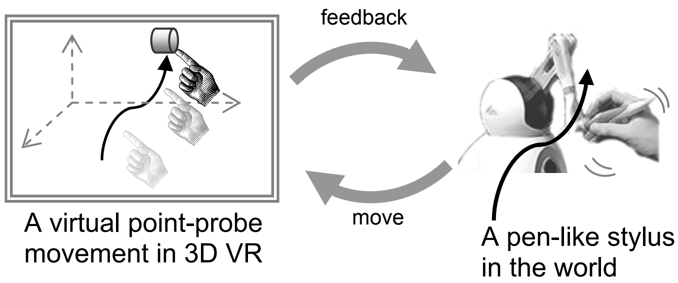


Figure 13. Simulated view of the use of a PHANToM™ haptic device

Haptic technology has several advantages over traditional tactile diagrams (e.g., Braille), including dynamism to construct graphs, flexibility to change graphs, durability, and easy-to-store data in a digital form (Yu et al., 2003). A number of researchers developed and demonstrated the effectiveness of haptic-based graphs. For instance, Yu (2002) presented a virtual wall system that was constructed by applying an enclosure and rectangle effect (see Figure 14). A pre-defined area, such as rectangular and elliptical shape, is designed to constrain mouse movement within the area. In contrast, the rectangle effect enables users to exit the enclosed area, which is accomplished by pushing the mouse harder against the resisting force.

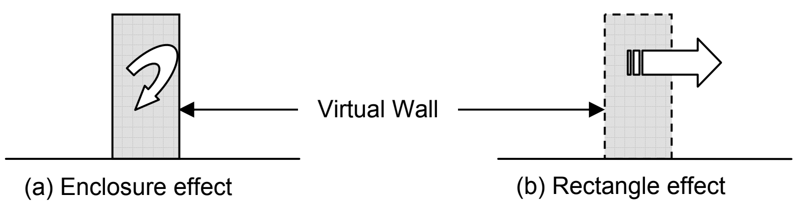
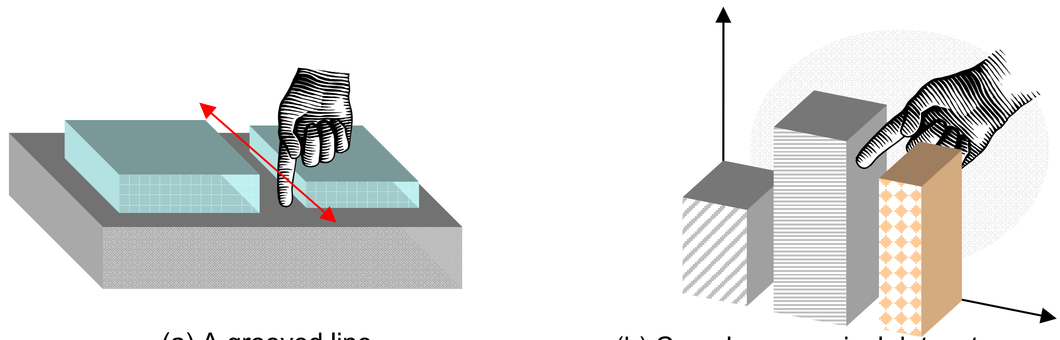


Figure 14. A virtual wall with (a) the enclosure effect (constrained), and (b) the rectangle effect (penetrative)

Additionally, a grooved line is often applied in presenting graphs to promote awareness of trends in complex numerical datasets. As shown in Figure 15, users following the grooved line are able to save time by locating reference points and minimizing confusion within the virtual environment (Yu et al., 2003). Compared with Braille, those using haptic technology can prevent themselves from losing contact with the lines of the diagram. Additionally, each dataset (presented as a bar graph on the right side of Figure 15) can be represented with different textures so that users have another cue to distinguish between the datasets easily.



(a) A grooved line (b) Complex numerical datasets

Figure 15. A simulated image of (a) the use of the grooved line to represent (b) complex numerical datasets

2.6. Low vision in the elderly

The majority of the literature on assistive technology has been oriented towards total blindness rather than low vision. Jacko et al. (2003) also observed that many researchers in the HCI domain have focused on the development of tools and devices primarily for users with total blindness. In fact, there are almost three times as many people with low vision than people with total blindness (Jacko et al., 2003). Low vision is more common among the elderly (aged 65 and older) as a result of age-related macular degeneration (AMD), glaucoma, diabetic retinopathy, or cataracts (Center for Persons with Disabilities, 2008; Horowitz, Brennan, Reinhardt, & MacMillan, 2006) (see Figure 16). AMD results in a loss of vision in the center of the visual field due to damage to the retina. AMD is one cause of severe visual impairments in individuals 65 years and older and affects approximately two million Americans (Carbonell & Stephanidis, 2003; Jacko et al., 2003) Glaucoma causes permanent damage to the optic nerve, which results in visual field loss. In general, diabetic mellitus leads to diabetic retinopathy that causes blurred vision. A cataract is caused by a clouding in the lens of eyes, which results in blocking the passage of light.

Macular Degeneration | Glaucoma | Diabetic Retinopathy | Cataracts

Figure 16. The same view as seen by the elderly with low vision because of age-related macular degeneration, glaucoma, diabetic retinopathy, and cataracts (photos by author)

More attention should be focused on elderly individuals with low vision. For instance, Individuals over 65 years of age represent a growing proportion of the U.S. population (Virginia Assistive Technology System, 2004). The number of individuals aged 65 and older increased to more than 34.6 million in 2000 compared to 3.1 million in 1990 (US Census, 2000). The number of people in all age groups 65 years and older consistently increased during this period, except for the population aged 65 to 69 years old (see Figure 17). The declining trend in the 65-to-69 age group reflects the relatively low number of births in late 1920s and early 1930s (US Census, 2000). The population of 56 to 69 years olds will increase in 2011 as the baby boomers, born from 1946 to 1964, turn age 65. The elderly will likely comprise a significantly larger proportion of the population by the year 2020 (Dewsbury et al., 2006). Of the people who have lost their vision, two-thirds are over the age of 65 (Ross, 2004). Consequently, it is anticipated that the number of older adults with low vision (i.e., severe and moderate visual impairments) will increase dramatically in the future (Burggraaff et al., 2006). In addition, WHO survey in 2002 indicated that older adults (50 years and over) accounted for the majority of people with blindness (Resnikoff et al., 2004). The survey included people with blindness in 17 WHO epidemiological sub-regions: Afr, WHO African region, Amr, WHO region of the Americas, Emr, WHO Eastern Mediterranean region, Eur, WHO European Region, Sear, WHO South-East Asia region, and Wpr, WHO Western pacific region. Approximately 1.4 million people below the age of 15 years have blindness, which is indeed small compared to the number of older people with blindness. According to the survey, more than 82% of the population with blindness are older people (50 years and over) (see Figure 18).

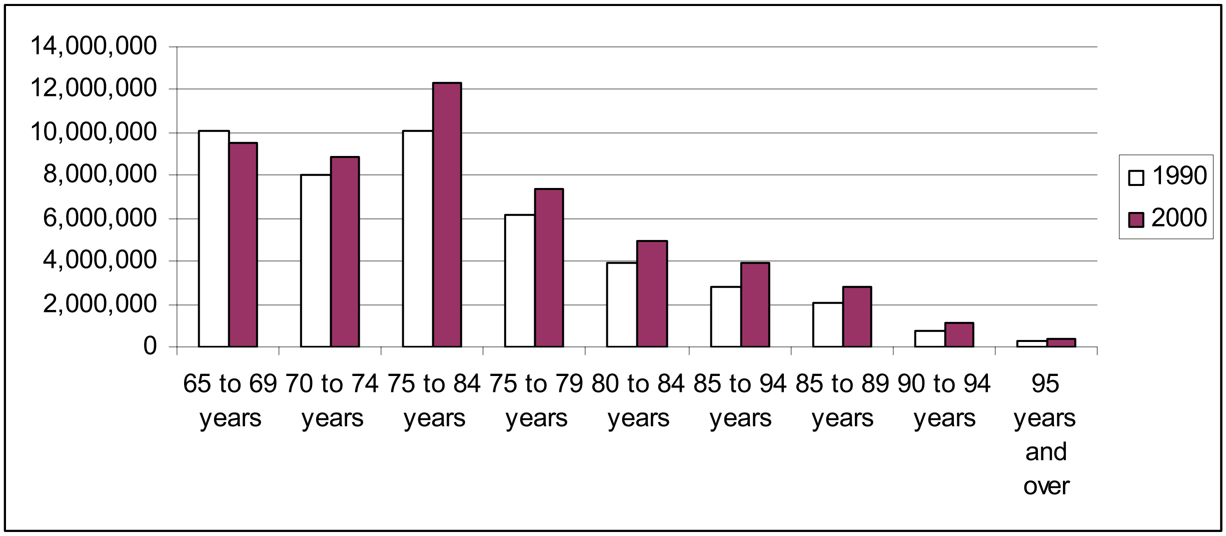


Figure 17. Population 65 years and over: 1990 and 2000 (created by author based on data from the U.S. Census Bureau, 2000) [public domain]

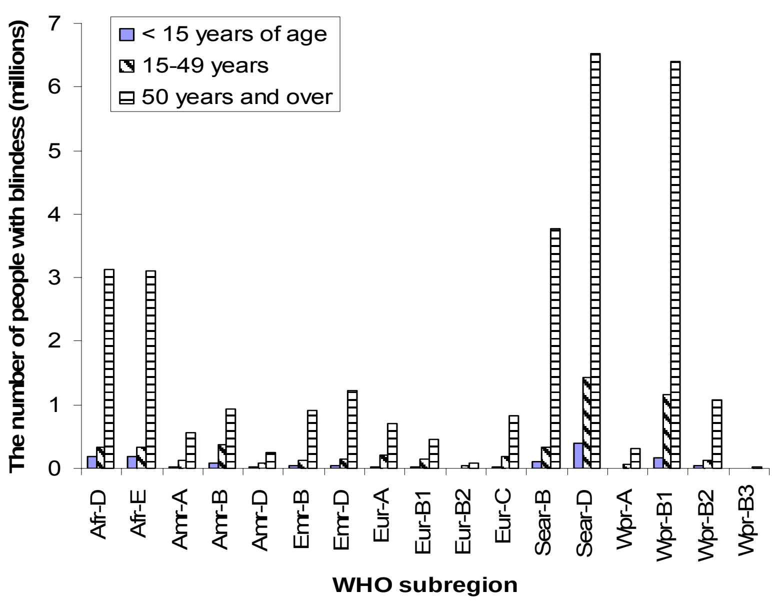


Figure 18. The number of people with blindness by age and WHO sub-region [public domain]

Assistive technology is a powerful tool for the elderly to achieve greater independence in everyday life. Today, there are 23,000 assistive technology applications available, the number of which is also rapidly growing (Virginia Assistive Technology System, 2004). Riemer-Reiss (2000) claimed that 13.1

million Americans obtain benefits from some type of assistive technology applications to accommodate for their own physical disabilities. Twenty three percent of elderly people take advantage of assistive technology devices (Hartke, Prohaska, & Furner, 1998), from the very simple to the complex. Simple applications include eyeglasses, large print materials, and screen-magnifiers for computers. Complex devices include modified hand controls for cars and wheelchair lifts. It is difficult to ignore older adults' demands for assistive technology and their preferences for user interfaces.

Older adults with low vision can also be the target user group for haptic technology. Older adults are assisted in everyday life by haptic devices (Baccini et al., 2006; Virginia Assistive Technology System, 2004). For example, accessing and seeing light switches is enhanced by touch-sensitive switches. A stove timer in the kitchen can be replaced with a timer that generates vibration. Individuals become more cautious about what they touch rather than what they see (MacLean, 2000). The sense of touch contributes to a variety of perceptual functions such as (1) assessments of an object's dynamic and material properties (e.g., texture and weight), (2) verification of engagement and completion (e.g. automobile gear shifting), (3) continuous monitoring of ongoing activity and gradual change (e.g., pencil sharpener), (4) building mental models for invisible parts of a system (e.g., recognition in darkness), and (5) judgments of other people (e.g., handshake) (MacLean, 2000). Examples of haptic technology applications for the elderly include an omni-directional mobile wheelchair with a haptic joystick (Urbano et al., 2005), an intelligent walker with haptic handle bar (Shim et al., 2005), and vibrating insoles for balance improvement of the elderly (Priplata et al., 2009). However, very few studies have considered the inclusion of older individuals with low vision in haptic technology design. This research gives priority to the needs of older individuals with low vision.

2.7. Abandonment of assistive technology

Unfortunately, many users are dissatisfied with their assistive devices. For example, a national survey on technology abandonment found that almost one-third (29.3%) of all the devices previously used were completely abandoned (Phillips et al., 1993). Goodman et al. (2002) stated that this abandonment mostly occurs within the first three months of use. Unfortunately, such dissatisfaction is likely to cause discontinuance of assistive technology devices. Concern about the abandonment of assistive technology applications remains important to today's researchers (Hoppestad, 2007; Riemer-Reiss, 2000; Riemer-Reiss et al., 2000). For instance, Sapp (2007) claimed that people with visual impairment often do not use assistive technology because it is not easy to use and also is not flexible enough to meet their needs. In particular, a recent study indicated that the haptic technology adoption rate is low (Bjelland et al., 2007). Discontinuing the use of assistive technology devices will ultimately result in a waste of time, money, freedom, and loss of function in individuals with disabilities (Phillips et al., 1993; Riemer-Reiss, 2000). Previous studies on assistive technology abandonment can be categorized into three groups: (1) users' personal characteristics, (2) technology acceptance, device attributes consumers prefer, and (3) device utilization surveys (Phillips et al., 1993). The primary factors causing abandonment include lack of consideration for user opinion, poor device performance, ease of device procurement, and changes in user needs (Phillips et al., 1993). Of all the factors that lead to abandonment, however, the most significant is the failure to meet users' needs (Riemer-Reiss, 1999). One intended user with a disability complained as follows:

> "Talk to the user. Be a little more considerate of the end-user. Don't assume anything. Ask the consumer. Listen to me! I know what works for me (Phillips et al., 1993. p 42)."

This research sheds doubt on the existing design approaches to assistive technology application development; design approaches fail to reflect assistive technology users' needs correctly. Thus, a more detailed investigation of design approaches, especially for haptic user interfaces, should be conducted.

2.8. Life cycles in user interface design

Today, Jakob Nielsen's usability engineering model is widely used in the HCI domain (Nielsen, 1992). The model consists of three phases of software development or user interface design: (1) pre-design, (2) design, and (3) post-design (see Figure 19). The first phase, pre-design, is designed to understand the target users and the tasks they wish to perform. The second stage aims to develop a prototype that meets usability principles and conduct a validation study with intended users. After the second phase, a product is released. The primary objective of the third phase, post-design, is to collect data for the next version and new future products.

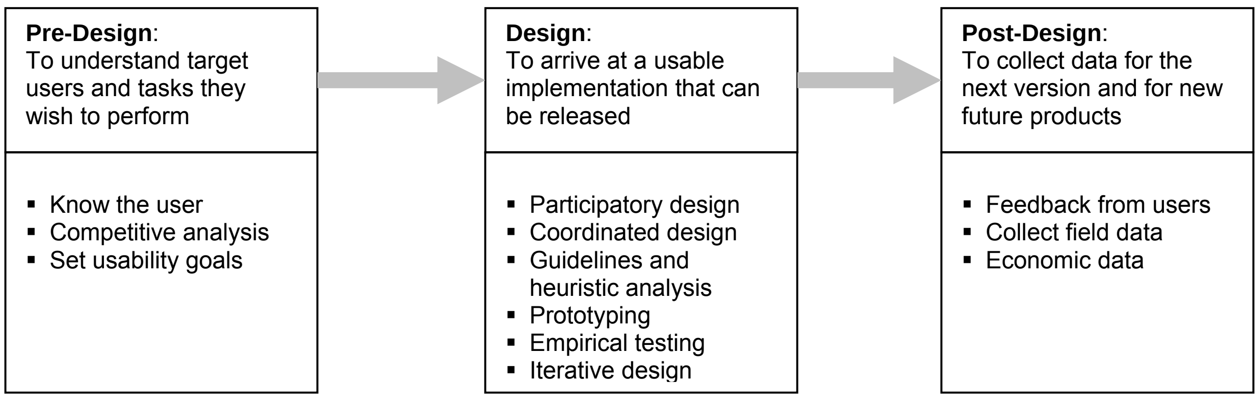


Figure 19. Usability engineering

In other words, user needs are first recognized through user needs elicitation methods. Afterward, the user needs are analyzed to construct a set of design guidelines (Nielsen, 1992). Based on the design guidelines, a released version of the product is developed. Because this research mainly focuses on whether the needs of users with disabilities are correctly reflected in the final product, it only partially addresses Nielsen's usability engineering model; that is, target users (chapter 2.9) and user needs elicitation (chapter 2.10). Therefore, a validation test of the prototype, or released version of the product, is excluded from this research.

2.9. Target users

This section begins with a discussion about what kinds of efforts have been made to improve accessibility for people with visual impairment. Additionally, the possibility that there are individual differences among people who share the same category of disability (i.e., visual impairment) is discussed. Their perception of the world and its relationship with the individual differences are explored as well. Afterward, the effect of age on these individual differences is discussed. The remaining chapters are devoted to an investigation of target user groups' capabilities in the haptic modality.

2.9.1. Efforts in accessibility

Technology has provided numerous, valuable information to people, but has also created barriers that inhibit access to people with disabilities, as well as older people. Many HCI researchers and practitioners have attempted to enhance accessibility for the past 20 years (Keates et al., 2002). In the U.S., the barrier-free design approach emerged during the civil rights and disability rights movements, which protects people with disabilities from discrimination (Keates et al., 2000; Keates et al., 2002). The barrier-free design approach led to the development of Section 504 of the Rehabilitation Act (US General Services Administration, 2008b), Section 508 of the Workforce Investment Act (US General Services Administration, 2008a), and the Americans with Disabilities Act or ADA (Kelly, 1995; US Department of Justice, 2008). The detailed relationships among and definitions of Section 504, Section 508, and ADA are described in Figure 20. Section 504 was the first legislative effort to ensure equality for individuals with disabilities. Section 508 provides detailed requirements with regard to technology design provide access to people with disabilities. ADA also prohibits discrimination based on disability in employment, public accommodations, commercial facilities, transportation, and telecommunications.

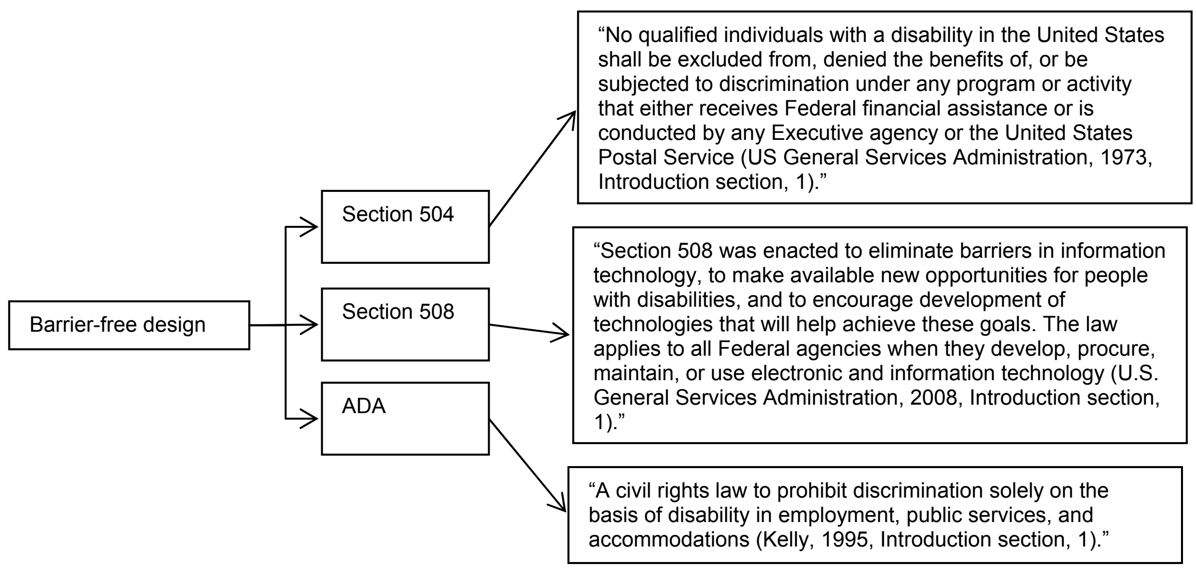


Figure 20. The barrier-free design approach included Section 504, Section 508, and the ADA

In addition, a variety of design approaches were launched to promote accessibility design, which included “Rehabilitation Design”, “Design by Story-Telling”, “Transgenerational Design”, “Universal

Design", "User Pyramid Design Approach", and "Inclusive Design" (Keates et al., 2002; Newell et al., 2000). Various aspects of these design approaches are compared and summarized in Table 5.

Table 5. Design approaches that are specifically focused on supporting accessibility

Design Approach	Design Aspects	Design Limitations	References
Rehabilitation Design	Developing solutions for people with severe disabilities in their daily life and elderly people	Released products were not qualified enough to satisfy the needs of users Accordingly, a majority of intended users did not purchase the products.	(Buhler, 1998; Gardner, Powell, & Page, 1993; Keates et al., 2002)
Design by Story-telling	Visualization of possible design solutions especially for older users	Lack of awareness in users with disabilities Difficult for designers to comprehend what it is like to be old.	(Keates et al., 2002; Moggridge, 1993)
Transgenerational Design	Product design that enhances the quality of life for users of all ages	Lack of awareness in users with disabilities	(Keates et al., 2002; Pirkl, 1994)
User Pyramid Design	Design process by sorting target users based on their capabilities (i.e., severely impaired, reduced strength, or fully capable). Issues related to aging and disabilities are covered.	Design begins by accepting the concept that this design approach cannot satisfy all and should exclude certain groups of users.	(Keates et al., 2002)
Inclusive Design	Product designed for the largest possible population, but not the entire population	It is more likely to restrict users to those who are merely providing their experiences.	(Keates & Clarkson, 2003b)
Universal Design	One-product-for-all types design to satisfy all users	It is nearly impossible to achieve from a practical point of view	(Jhangiani, 2006; Keates et al., 2002; Kyoko, 2005; Nicolle & Abascal, 2001)

Rehabilitation Design emphasizes the needs of elderly people and people with severe disabilities. However, intended users were dissatisfied and tended to abandon design solutions for several reasons, including functionality, usability, quality, and safety problems (Gardner et al., 1993). Mahoney (1997) comprehensively reviewed 10 rehabilitation robot products commercially available across the U.S., the UK, France, and Canada to identify those factors that prevented or slowed the development of products for people with disabilities. Outstanding factors were poor user interfaces, isolation from clinical reality, too expensive, lack of portability, poor organization, and lack of sufficient capital. Another design approach, Design by Story-telling, is achieved by understanding the nature of aging, observing older users' activities, exploring design solutions, and evaluating suggested design solutions (Keates et al., 2002). However, this design approach does not take into account users with disabilities. Transgenerational Design also emphasizes the issue of age, but focuses on developing a product that works for users of all ages from young to old (Keates et al., 2002). However, this design approach also does not consider users with disabilities. On the other hand, User Pyramid Design is applied by taking into account users' age and impairments. This design approach is based on the assumption that if a product is designed to be accessible by a particular group of users, the resultant product will also be accessible by users with less severe or no impairments. Such a claim implies that a certain group of users will be excluded in developing design solutions. Inclusive Design was influenced by the claims of User Pyramid Design. Inclusive Design aims to design a product for the largest possible population, but not the entire population. Universal Design is defined by the Center for Universal Design at North Carolina State University as "the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design (The center for universal design, 1997)." Accordingly, seven design principles were also developed, including (1) equitable use, (2) flexibility in use, (3) simple and intuitive use, (4) perceptible information, (5) tolerance for error, (6) low physical effort, and (7) size and space for approach and use. Sapp (2007) asserted that developing technology by applying the principles of Universal Design can remove many barriers to access. For example, audio descriptions were embedded in a system to enable users with visual impairment to access visual information (Sapp, 2007). Inclusive Design and Universal Design (or Design for All) appear similar, but they are distinct (British Standards, 2005). The Universal Design approach is often employed to make a single product by aiming to satisfy all users, including those with disabilities. However, the 'one-product-fits-all' type approach is currently viewed as nearly impossible to achieve (Abascal, 2002; Jhangiani, 2006; Kyoko, 2005; Newell et al., 2000; Nicolle et al., 2001). On the other hand, Inclusive Design considers the needs of a wider range of users. Inclusive Design typically emphasizes a product designed for the largest possible population, but not the entire population (Clarkson, Keates, Coleman, Lebbon, & Johnston, 2007; Keates & Clarkson, 2003a; Keates et al., 2003b). However, it lacks a systematic, 'human factors' design protocol. Furthermore, Inclusive Design is more likely to restrict users to those who are merely providing their experiences.

Various regulations (e.g., Section 508) and design approaches were explored to see how they contributed to accessibility designs for users with special needs. However, a key question that should be addressed is whether the regulations and the design approaches investigated the existence of heterogeneous needs among users who share the same category of disability. In fact, based on the literature reviews, these regulations and design approaches have rarely considered the individual differences among users traditionally classified in the same category of disability.

2.9.2. Individuals with varying visual impairment

In user interface designs for individuals with disabilities, one concern is associated with the presumptive design approach. Designers tend to assume that there are no individual differences among users in the same category of disability. Most existing design approaches primarily focus on the different needs of users with and without disabilities (Douglas et al., 2007; Sjostrom, 2001a; Sjostrom et al., 2003). The comprehensive literature review presented here focuses particularly on accessibility and usability for people with visual impairment (see Table 6). Most previous studies fall into three categories based on the comparisons that were made: (1) between participants with sight versus those with visual impairment, (2) among participants with varying degrees of visual impairment, and (3) among participants with the same type of visual impairment.

Table 6. Accessibility and usability studies related to users who are visually impaired

Focus	Study	Participants	Investigation of individual differences	Approach	System	Reference
Between those sighted and those visual impaired	Multimodal interactions with visual and audio cues	5 individuals with sight and 5 with blindness	Study on the differences between participants with sight and blindness	User-centered design: Evaluation (observation of users interacting with a released product)	CAPCHA (Completely Automated Public Turing tests to tell Computers and Humans Apart)	(Holman, Lazar, Feng, & D'Arcy, 2007)
	Haptic comparison of size	11 individuals with sight and 11 with blindness	Study on the differences between participants with sight and blindness	User-centered design: Evaluation (time and accuracy)	PHANToM haptic device	(Douglas et al., 2007)
	A target-route map's usability	24 individuals with sight and 4 with visual impairments	Study on the differences between participants with	User-centered design: Evaluation (reading time and recall capability of	Target-route map system	(Harder et al., 2002)

			sight and blindness	the map)		
	E-learning and blindness	10 individuals with sight and 10 with blindness	Study on the differences between participants with sight and blindness	User-centered design: Evaluation (time taken to complete, learning performance, and satisfaction)	Online educational Web site	(Evans & Douglas, 2008)
Among those with various visual impairments	E-commerce Web accessibility	Unidentified number of individuals with blindness and low vision	No, all data from participants with various visual impairments were combined	User-centered design: Focus group	Web page overview function	(Bergel, Chadwick-Dias, & Tullis, 2005)
	Assistive technology computer use	In total, 41 individuals with blindness or visual impairments	No, all data from participants with various visual impairments were combined	User-centered design: Focus group	Computer related to assistive technology and Web	(Gerber, 2003)
	Fully accessible online scheduling tool	10 individuals with blindness and 2 with low vision	No, all data from participants with various visual impairments were combined	Universal design: Universal design principles were applied. Observation of users' performances.	HTML-based Web site	(Sapp, 2007)
	Talking tactile tablet in mathematics tests	In total, 8 individuals with no useful vision, some useful vision, considerable useful vision, and limited useful vision	Ambiguous data analysis (unwilling to show the source of users' comments), e.g., some described, two participants indicated	User-centered design: Focus group	Audio-tactile computer peripheral device (called talking tactile tablet)	(Gerber, 2002)
Single type of visual impairment	Multimodal renderings of mathematical information	4 individuals with blindness	none	User-centered design: Evaluation -think aloud & NASA TLK	Mathtalk (interface for reading algebra using speech)	(Stevens, Edwards, & Harling, 1997)
	Auditory interface	7 individuals with visual impairments	none	User-centered design: Evaluation (structured interview)	Soundtrack (i.e., a word processor with an auditory interface)	(Edwards, 1989)
	Interaction with the Internet through a self-voicing application	An individual with a detached retina in the right eye.	A single participant involved	User-centered design: Evaluation (observation of users performances)	A self-voicing application for seeking information on the Internet	(Jones, Farris, Elgin, Anders, & Johnson Brian R, 2005)
	Usability problems of screen-reading technology	13 individuals with no useful vision	none	User-centered design (observation)	JAWS screen-reading technology	(Barnicle, 2000)
	A gestalt understanding of a Web page quickly	6 individuals with visual impairments	none	User-centered design (think aloud assessments)	AcceSS (Accessibility through Simplification and Summarization)	(Hackett & Parmanto, 2006)
	Enhanced curriculum for children with disabilities	9 individuals with visual impairments	none	User-centered design (observation and focus group)	A science curriculum, PSCD (Playtime Is Science for Children with Disabilities)	(Erwin, Perkins, Ayala, Fine, & Rubin, 2001)

In the first type of study (i.e., in sight and visual impairments), a target systems' accessibility was generally enhanced by focusing on identifying and accommodating different needs of users with visual impairment compared to users with sight. Unfortunately, no further investigation was typically made to examine individual differences among the participants with visual impairment. In the second type of study (i.e., among those with various types of visual impairment), some studies distinguished participants by the degree of visual impairment; however, most did not. Instead, all data (e.g., users' comments and behaviors) were merely combined. Surprisingly, the majority of prior studies did not state how they defined and classified the participants' vision. Ideally, they should have quantitatively measured participants' vision by using, for example, a Snellen chart to sort the participants into two groups: those with severe visual impairments versus those with moderate visual impairments. Even if the authors of these studies had claimed that there were differences in the participants with different degrees of visual impairment, it is not entirely clear how many participants were distinct in terms of their vision. In one study, for instance, participants were arbitrarily sorted and their vision was described as 'no useful vision,' 'some useful vision,' 'considerable vision,' and 'limited useful vision' (Gerber, 2002). In the third type of study, participants had the same type of visual impairment, but the differences among them were not explored. Given this review of the literature, it can be stated that little attention has been paid to the individual differences of users in the same disability category.

It has recently been discovered that people with the same disability often have different views on a certain issue (Luck, 2003). Dulin (2007), for instance, reported that individual differences were observed among those who were different ages at the onset of their blindness. People who had been diagnosed as totally blind by 6 months of age usually made more errors (error rates ranged from 0% to 28%) compared to people who had become totally blind by approximately 15 years of age (error rates ranged from 0% to 15%). They responded differently to external environments or circumstances. Consequently, those with early-onset blindness should be given a user interface that is accordingly customized to enhance their performance.

Such different performance outcomes were also detected in people with different degrees of vision loss (Blanco et al., 2003; Jednorog et al., 2008; Plimmer et al., 2008). In a recent study (Plimmer et al., 2008), the existence of different preferences for user interactions with a force-feedback system (i.e., PHANToM™-based drawing system) were recognized in participants with blindness and those with partial vision. In contrast with partially sighted participants, participants with blindness, for example, always used both hands; they held the PHANToM™ stylus in one hand and used the other to keep their orientation within the workspace (i.e., a drawing board) and simultaneously felt the tactile marks created by the stylus. Thus, these two groups of participants showed different patterns of interaction with the same system. Additionally, Blanco and Travieso (2003) conducted a well-known experiment, involving a fictitious island (Kosslyn, Ball, & Reiser, 1978) in which they studied haptic exploration and mental estimation of distances on a fictitious island involving three groups: those with blindness, low vision, and sighted people who were blindfolded. Participants with blindness took fewer trials (mean = 1.6) to complete the haptic exploration task compared to those with low vision (mean = 2.3). The amount of time participants with blindness used to explore the island was shorter (1.3 minutes) than in those with low vision (3.25 minutes). Thus, these two types of participants with different degrees of vision loss performed the same task differently. To gain a better understanding of such individual differences among people with various visual impairments, we should first discuss a fundamental issue: the mental model of those whose vision is impaired. In the following chapter, how those with visual impairments interact with the real world will be explored.

2.9.3. Direct and indirect perception theories and people with visual impairment

Before discussing the mental model of people with visual impairment, one question should first be answered: Do people with visual impairment 'have' a mental model of their environment? Psychologists have argued about how human beings interact with their environment. In general, people use their sense organs (e.g., eye) to receive input with regard to the environment. The physical sensory input is then converted into perceptions of, for example, desks and computers. The conversion process leads to the psychologists' arguments. There are two distinct views about human perception. First, Gibson (1979) claimed that perceptual processes are direct. In contrast, Gregory (1997) argued that perceptual processes are indirect.

Gibson saw that perception is direct and not related to hypotheses testing. He believed that human beings can interact with the world in a direct way, requiring little or no knowledge because there is enough information (e.g., size, shape, and distance) in our environments (Gibson, 1979). Thus, there is no need for interpretation processing. Gibson's theory introduces, for example, optic flow patterns and affordance (McLeod, 2007). More specifically, Gibson asserted that a change in the flow of an optic array gives critical information with regard to what type of movement is occurring. In Figure 21, a perceiver is on a train moving toward (left image) and away (right image) from a reference point. If flow appears to be coming from a particular point, it implies that the perceiver is moving toward that point. If a perceiver is in the opposite position, it means the perceiver is moving away from that point.

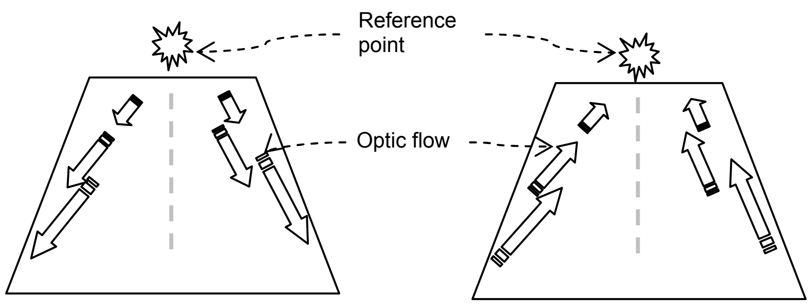


Figure 21. Optic flow patterns: A perceiver is moving toward (left) and moving away from (right) a reference point (constructed by author)

In addition, the concept of direct perception is facilitated by 'affordances,' which are cues from the environment. Importance cues can be an optical array, relative brightness, texture gradient, relative size, superimposition, and height in the visual field. However, Gibson's direct perception theory cannot explain illusions. What we see is quite often not present in the actual visual stimulus. There are four different types of illusions: distortions, ambiguities, paradoxes, and fictions (Gregory, 1997). As shown in Figure 22, one line appears to be longer than the other; however, they are, in fact, the same length.

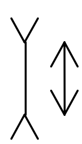


Figure 22. Muller-Lyer illusion (Müller-Lyer, 1889) [public domain]

People generally create two alternative hypotheses when looking at the Necker cube shown in Figure 23. Depending on one's focus, people satisfy one of two hypotheses.

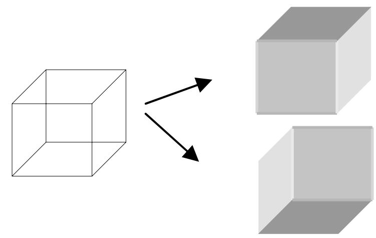


Figure 23. Necker cube and two alternative hypotheses depending on the perceiver's focus (Necker, 1832) [public domain]

The Kanizsa's triangle in Figure 24 is the most distinct example that offers an absence of signals. A triangle appears to be located inside, but it is not physically present. The triangle's appearance is influenced by the rest of the configuration.

[Deleted due to copyright]

Figure 24. Kanizsa triangle (Kanizsa, 1955)

One's perception of the parts of a stimulus is influenced by the overall stimulus configuration. Gregory stated that a perception is not simply determined by stimulus patterns, but rather it should be regarded as a dynamic searching for the best interpretation of available data (McLeod, 2007). It is difficult to accept that Gibson's direct perception theory fully explains how people with blindness interact with the environment. First, Gibson's direct perception theory is based on the notion that perception is constructed from information coming from the retina. People with blindness do not rely on the retina when interacting with the environment. Gibson's theory denies the phenomena of illusion. Illusion is represented by an absence of visual signals. People with blindness do not obtain any visual signal about an object in the world, but instead touch an object over its surface and seek data available in the environment. They gather all data and interpret what it looks like, which is similar to a puzzle game in which they find the puzzle pieces and fit them into the proper location in the puzzle. In other words, they conduct a dynamic searching that is indirect, top-down, and an interpretive approach, which is consistent with Gregory's indirect perception theory. In Gregory's indirect perception theory, visual information (i.e., retinal images) are viewed as ambiguous with regard to size, shape, and the distance of objects from each other

(Gregory, 1997). In addition, indirect perception theory asserts that vision lacks the capability to signal many properties (e.g., hardness, weight, hot, cold, edible, and poisonous) that indeed affect behavior. Gregory defines perceptions as hypotheses in which unsensed features of objects are predicted, and the prediction occurs in time to compensate for neural signaling delay. Such hypotheses are typically structured, based on one's experiences, and stored information. Kurze (1996) applied Gregory's indirect perception theory to develop a computer-based tactile drawing tool for people with blindness. For example, people with blindness adopt sensory information (touch) and generate a corresponding mental model (object image). The mental model in turn causes action (drawing) (see Figure 25).

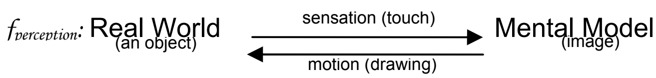


Figure 25. Relationship between the real world and the mental model for people with blindness

2.9.4. Mental model of people with visual impairment

A mental model can simply be considered a set of ideas on how a system works. People form mental models for themselves and of things with which they are interacting. A certain conceptualization that people develop and keep, in turn, governs their views (1) of the world, (2) of themselves, (3) of their own capabilities, and (4) of the tasks they are asked to do or something they attempt to learn (Norman, 1983). As shown in Figure 26, there are four different aspects relevant to a mental model: a target system, a conceptual model of that target system, a user's mental model of the target system, and a scientist's conceptualization of that mental model (Norman, 1983).

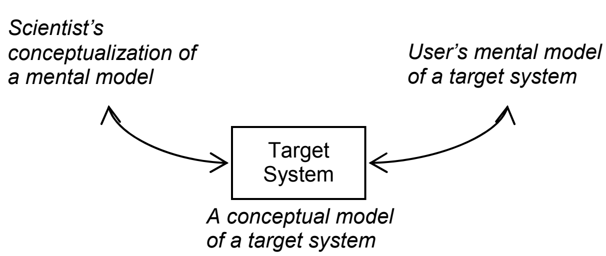


Figure 26. Four aspects related to a mental model (reproduced from Norman, 1983)
[Used with permission from MIT Press, see APPENDIX G]

- Target system: A system with which people interact
- Conceptual model: A model that is made to appropriately represent the target system

- Mental model: A model that is invented by a user interacting with a target system
- Conceptualization: A scientist's conceptualization of a mental model (i.e., a model of a model)

As shown in Figure 27, a mental model is run by mental image(s) and a set of possible actions (Kurze, 1996). Human perception functions to fit sensory-received information (i.e., stimuli) from environments into an existing internal idea (i.e., mental image). The mental image also serves as a data structure linked to a set of possible actions. For instance, if a certain stimulus does not fit, the mental model is changed.

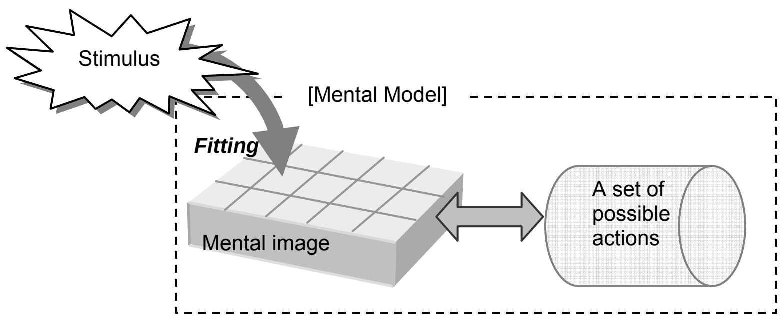


Figure 27. A schema of a mental model

Mental models are closely related to the field of usability. A mental model serves as knowledge that users have about how a system works; its component parts; their interactions; and how one component affects another (Fein, Olson, & Olson, 1993). Ideally, as shown in Figure 26, a scientist's conceptualization of a mental model and a user's mental model of a target system are equivalent (Norman, 2005). An inaccurate mental model leads to errors. For example, a door handle is supposed to be pulled by a user to enter a room. However, what the user actually did was to push the door handle because the design of the handle gave the user the impression that the door should be pushed. The user and the designer did not have the same mental model of how the door should work. Mental models play a critical role in a usability study in helping users correctly interpret a system's actions and predict commands (Kurniawan et al., 2003). In short, mental models support human reasoning in three ways: prediction, justification, and remembrance (Williams, Hollan, & Stevens, 1983). People can use mental models as inference engines to predict how physical systems work. Additionally, mental models can be used to facilitate explanations or justifications. Mental models can also assist people in remembering something or someone.

Do individuals who are visually impaired have the same mental models of the real world as those who have no visual impairment? Kurze (1996) claimed that people with blindness and those with sight have very similar mental models of the real world (see Figure 28). According to his argument, a mental model inherently contains all relevant features of the real world, as well as the 'referent' of mental models that the two groups possess that is the same; that is, of the real world. Consequently, when asked about spatial information (e.g., position, orientation, and size) of certain objects in the same world, both groups of people provide the same answers. Based on this logic, Kurze concluded that people with blindness have the same mental model as sighted people. However, Kurze only considered the *final* output of mental model processes (e.g., the same answers, same images). Unfortunately, Kurze ignored '*how'* people with blindness work through the processes related to mental model construction to get to the final output.

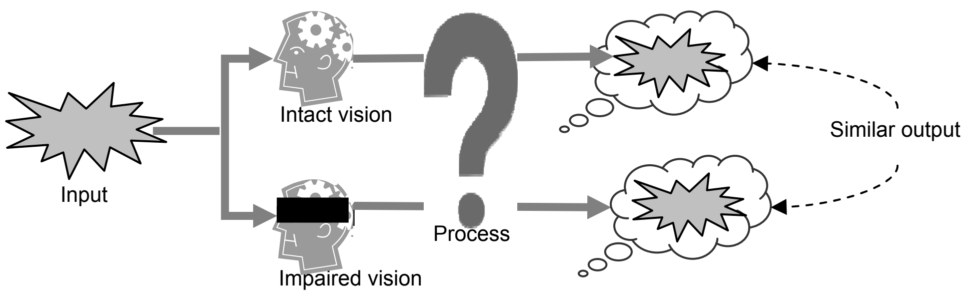


Figure 28. Kurze's point of view on mental models in people with intact vision versus those with impaired vision

Other researchers assert that people with visual impairment have different mental models from people with sight. For instance, Kurniawan et al. claimed that users with blindness and users with sight have different mental models with regard to computers and the Windows environment (Kurniawan et al., 2002; Kurniawan et al., 2003). Because sighted users rely heavily on their vision, they view the Windows environment as a set of visible objects and organized metaphors in a graphical space (e.g., menus, buttons, and icons). Sighted users are less influenced by the capability of memorizing commands. On the other hand, users with blindness normally memorize options to interact in the Windows environment. More specifically, based on interviews with computer users with total blindness or with some residual vision, Kurniawan et al. reported that they had three different types of mental models: a functional mental model, a structural mental model, and a combination thereof. A user with the functional mental model views the Windows environment as a place that is governed by keyboard shortcuts. A user with the structural mental model regards the Windows environment as a place that is composed of a strict column and row array of icons. A user can move between objects regardless of any geometrical structure. In addition to the functional and structural mental models, there is another mental model: the hybrid model. A user of the hybrid model thinks that the Windows environment is operated by a combination of keyboard shortcuts and layouts.

In addition, Millar (1994) claimed that there are individual differences in those with visual impairment and those who are sighted in terms of the way they code spatial information. In general, a mental model can contain information associated with temporal, spatial, causal, person-related, and object-related features of a particular event (Noordzij, Zuidhoek, & Postma, 2006). Vast amounts of research have considered the spatial aspects of mental models crucial for people who are visually impaired (Noordzij et al., 2006). The coding approach of people with visual impairment refers to a local, sequential representation based on a route strategy. For example, when people who are visually impaired read or listen to certain spatial information, they are more likely to rely on a sequential representation. On the other hand, the coding approach of sighted people is referred to as a more global, externally based representation.

According to Mayer's cognitive theory of multimedia learning (Mayer, 2003), people typically comprehend information through three cognitive processes related to sensory memory, working memory, and long-term memory (see Figure 29). The main goal of these cognitive processes is to enable an individual to construct a mental representation of an artifact. For example, information containing certain words and images is first recognized by one's ears and eyes. Afterward, an individual chooses some relevant aspects of the sounds and images. The relevant aspects will then be organized to build verbal and visual models. These verbal and visual models are integrated with relevant prior knowledge. A certain learning outcome is expected to emerge, which will be stored in long-term memory for future use. Mayer's model is based on the assumption that the working memory has dual channels: a visual and a verbal channel. Mayer's cognitive theory is also consistent with Baddeley's theory of working memory

(Jones, Minogue, Oppewal, Cook, & Broadwell, 2006). Baddeley's mental model (Baddeley, 2007) is composed of three components: (1) a central executive, (2) a phonological loop, and (3) a visuospatial sketchpad. The central executive serves as an attentional control system that deals with the flow of information from and to its subsidiary storage systems (i.e., the phonological loop and the visuospatial sketchpad). The phonological loop is responsible for holding acoustic information in temporary storage. The visuospatial sketchpad performs a similar function for visual and spatial information. Baddeley's mental model was recently modified by adding a new component, an episodic buffer (Baddeley, 2007). The new component facilitates a binding mechanism for information from the three working memory subsystems and long-term memory.

The main concern of this research is the function of sensory modalities, especially for people with visual impairment. If Mayer's cognitive theory is applied to people with visual impairment, it is expected that they would be unable to develop a visual model such that they consequently cannot gain rich information from environments, and probably encounter a challenge to understanding a given object (see Figure 29).

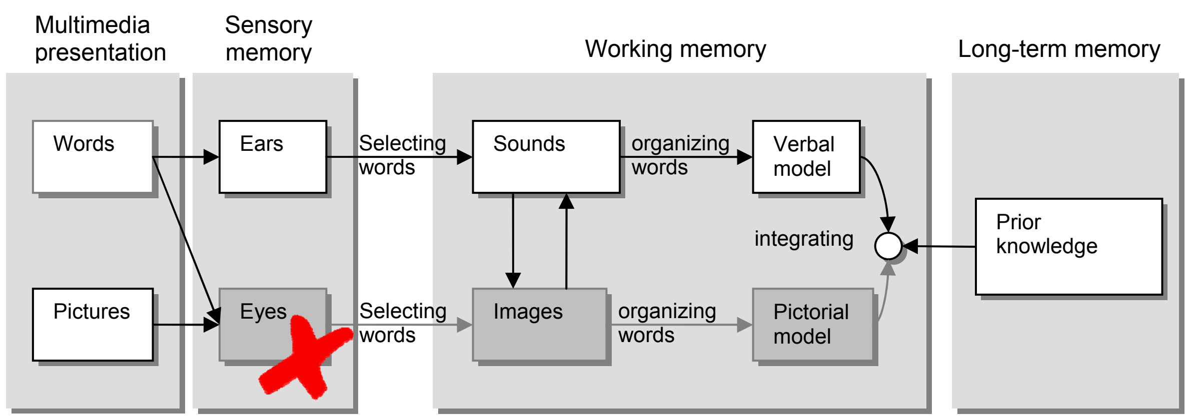


Figure 29. A framework of the cognitive theory of multimedia learning proposed by Mayer (2003) in which people with visual impairment are unable to obtain rich information from environments [Used with permission from Elsevier, see APPENDIX G]

Carneiro and Velho (2004) pointed out that people with blindness can instead rely on other channels to understand the world; for example, using the sense of touch, they can facilitate their understanding of the world (e.g., objects' shape, size, texture, and spatial position) (see Figure 30). People who are visually impaired develop certain spatial structures linked to a set of possible operations and also record relevant information (Carneiro et al., 2004). Such structures are referred to as people's mental models, which of course, are built by non-visual based senses. Even if people are congenitally totally blind, they can generate and process visuospatial images (Cornoldi et al., 2000). While a visual trace is directly from sight (or a visual experience), a visuospatial mental image is generated based on other sources of information, such as haptic, auditory, or long-term memory (Cornoldi et al., 2000).

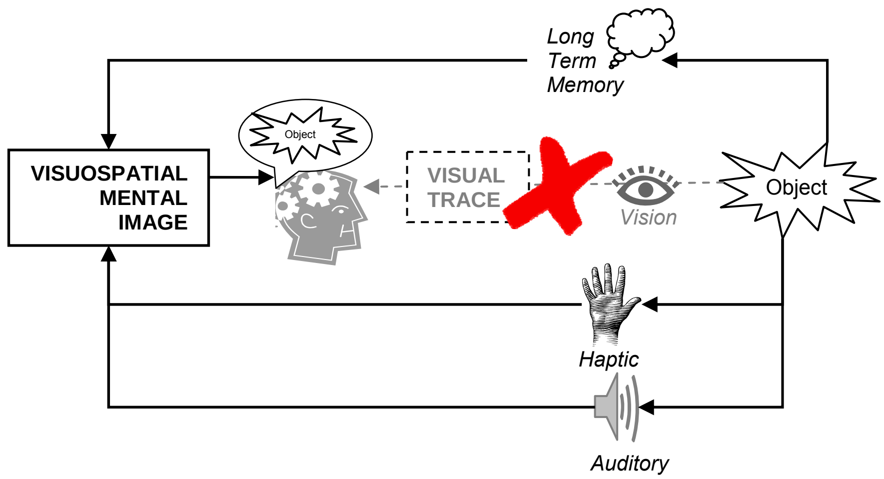


Figure 30. A schema of the construction of visuospatial mental images by people with total blindness

Consequently, people with blindness are expected to take advantage of the visuospatial mental image to recognize objects. Outputs induced by a visual trace (as in sighted people) and a visuospatial mental image (as in people with visual impairment) can appear to be different; they are derived from different processing mechanisms in terms of access, sources, attention, represented object, perception analogy, main characteristics, role of long-term memory, process penetrability, modality of loss, interference, capacity limitations, and age-related modifications (see Table 7) (Cornoldi et al., 2000).

Table 7. Differences between visual traces and visuospatial mental images (reproduced from Cornoldi et al., 2000)
[Used with permission from Oxford University Press]

	Visual traces	Generated images
Access	Direct	Generated
Sources	Visual perception only	Different modalities
Access for blind people	Impossible	Possible
Attention	Very low (pre-attentive)	Usually high
Represented object	Phenomenic object	Generated object
Perception analogy	Almost complete	Partial
Main characteristics	Sensorial/phenomenic	Perceptual/semantic
Role of long-term memory	Marginal	Substantial
Process penetrability	Almost none	Substantial
Modality of loss	Similar to sensorial processes	Similar to memory processes
Interference	Visual similarity	Similar processes, attentional request
Capacity limitations	Storage	Storage and processing
Age-related modifications	Minimal	Substantial

In general, visuospatial mental imagery is developed by reflecting upon different sources of information, which is completed in six steps (Heller, 2000, p. 145):

1. Activation of an image generation program based on task requirements.
2. Retrieval of the relevant information from long-term memory or from material temporarily stored in working memory. This process could be automatic or executed through an active search in the memory stores.
3. Construction of a general layout of the image.
4. Progressive enrichment, insertion of details and specific features.
5. Maintenance.
6. Further elaboration such as scanning, zooming, image modification, replacements, integration, subtraction, and change of perspective/rotation.

In summary, it is clear that people with visual impairment interact with the world though mental models that are constructed by using different sources (e.g., long-term memory, auditory, and haptic), which can be factors, in turn, that influence their behaviors in responding to the world. In the following section, the relationships between these factors and the behaviors of those with visual impairment will be explored in more detail. As argued earlier, the sensory homunculus in the somatosensory cortex is considerably corresponded by the sense of touch, which plays a critical role in how people with vision impairments communicate with the world. Consequently, this research pays particular attention to behaviors related to the sense of touch.

2.9.5. Heterogeneous haptic capability and interaction with haptic technology

Numerous studies have reported compensatory performance changes in individuals with visual impairment. As discussed previously, the performances of people with visual impairment in haptic-related tasks are superior to that of sighted people. This research attempts to understand this superiority by applying brain plasticity theory. Plasticity is considered an important characteristic of the human brain; the nervous system's gradual process of change and development to escape restrictions of its own genome (Pascual-Leone, Amedi, Fregni, & Merabet, 2005). The brain changes consequently facilitate the adaptation to environmental pressures and physiological changes. When an individual becomes visually impaired, for instance, the brain takes advantage of its plasticity and reorganizes existing connections between different cortices of the brain (Voss, Gougoux, Zatorre, Lassonde, & Lepore, 2008). Specifically, increased connectivity is often observed between the occipital and parietal lobes of individuals with visual impairment (e.g., blindness, severe visual impairment, or moderate visual impairment) (Burton et al., 2002). Surprisingly, the increased connectivity typically leads to enhanced abilities in the remaining modalities, such as haptic modality (Jednorog et al., 2008). For instance, superior performance in some sensory discrimination tasks is observed in individuals with visual impairment (Grouios et al., 2001). The brain plasticity theory implies that Braille readers with visual impairment become adept at tactile processes and effectively accomplish Braille reading tasks because of the increased connectivity between the parietal and occipital lobes of the brain (see Figure 31). Many researchers have empirically demonstrated different performance outcomes of a given task in people with visual impairment and in sighted people (Burton et al., 2002). In the following section, this research will review performances *among* people with different degrees of visual impairment.

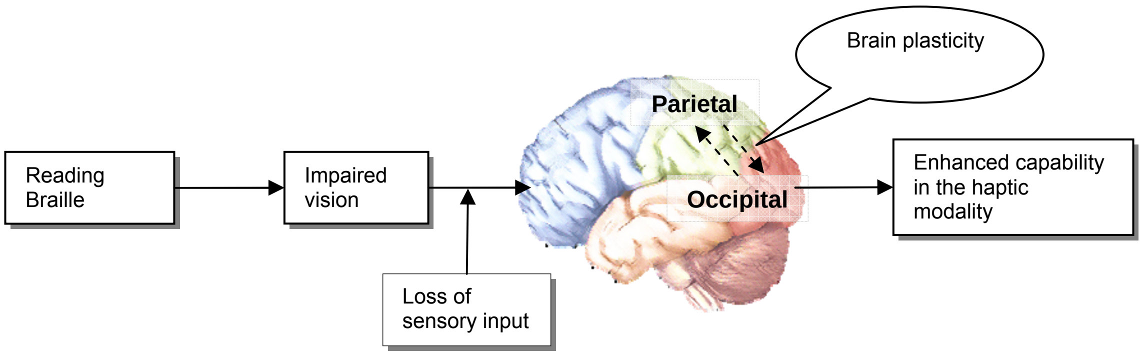


Figure 31. Scheme of brain plasticity

The onset of vision loss influences the degree of brain plasticity and capabilities in the remaining modalities (Hannan, 2006; Hatwell, Streri, & Gentaz, 2003). For example, participants with early- and late-onset blindness in Marmor and Zaback's study (1976) were instructed to compare two 3-D objects and state if they were the same image. The 3-D objects were randomly rotated specific degrees, such as 0°, 60°, 120°, or 180°. Some pairs of images were indeed identical. The results showed that participants with early-onset blindness took longer and made more errors than those with late-onset blindness. The same mental rotation test was conducted with individuals with congenital blindness and late-onset blindness (Kerr, 1983). Participants with congenital blindness took longer compared to participants with late-onset blindness. These empirical data support the notion that people with visual impairment can create and manipulate special representations, but their performance varies depending on their vision status. Participants in the studies described above differ in terms of the onset of visual impairment, which suggests that visual experience before vision loss likely influences their performance. Dulin (2007) conducted an interesting experiment to investigate the effect of visual experience on performance. Dulin compared individuals who were congenitally blind with those with early- and late-onset blindness in the accomplishment of certain tasks, such as estimating a length, mentallly representing the spatial displacement of a spot, and rotating an object in their mind. Dublin also studied the relationship of participants' performance with various levels of expertise in raised line materials. When participants had a high level of expertise in raised line materials, Dulin tagged those participants as experts. Results indicated that expert individuals who were congenitally blind outperformed non-experts with early- and late-onset blindness. Furthermore, expert individuals with early-onset blindness outperformed non-expert individuals with late-onset blindness. In short, the results of Dulin's experiment indicated that a high level of expertise in a certain task (e.g., a task associated with the sense of touch) compensates for the lack of visual experience, which is indeed consistent with other studies (Cattaneo, Vecchi, Monegato, Pece, & Cornoldi, 2007; Cornoldi et al., 2000).

There is confusion in the literature concerning the terminology of early-and late-onset blindness. Marmor and Zaback (1976) viewed those with early-onset blindness as those having been diagnosed with total blindness by 6 months of age, whereas those with late-onset blindness were defined as those who had become totally blind by approximately 15 years of age. Dublin (2007) categorized people who lost vision before the age of 3 as having early-onset blindness, but after the age of 3 years as having late-onset blindness. In another study (Voss et al., 2008), participants who became blind between 0 and 14 years of age were regarded as having early-onset blindness, while people who became blind between 18 and 37 years of age were regarded as having late-onset blindness. In Burton's study (2004), participants with late-onset blindness became blind at an average age of 21 years (from 6 to 41 years), but participants with early-onset blindness at an average age of 0.9 (from 0 to 5 years). Voss et al. (2004) viewed people with early-onset blindness as those who had lost their vision before they reached 11 years of age, but those with late-onset blindness were those who had lost their vision after 16 years of age. Participants with early blindness in Forster's study (2007) had visual impairment between birth and 2 years. Roder (2004) defined people with late-onset blindness as those who had become blind between 12 and 35 years of age. In sum, the studies above appear to classify participants as having early-onset blindness versus late-onset blindness arbitrarily. Other studies did not indicate the range of onset (Pascual-Leone et al., 2005). Because visual imagery is closely related to mental model construction in people with visual impairment, visual imagery can be used to determine the critical period for early- and late-onset blindness. In Jastrow's experiment (1880), individuals blinded after the age of 7 had visual imagery in their dreams, but individuals blinded before the age of 5 did not have dreams with visual imagery. Between the ages of 5 and 7 could be the critical period that distinguishes people with early- versus late-onset blindness.

Different brain activity patterns in people without or with visual impairment were discussed in previous sections of this document. People with visual impairment reorganize the brain to compensate for the loss of visual input. It was suggested that such a difference in brain activity was caused by brain plasticity, which would lead to enhanced capability in the haptic modality. In this section, whether different brain activity patterns are also observed in people with various types of visual impairment will be explored. Numerous studies have consistently shown that people with vision impairments, including congenital, early-, and late-onset blindness, show activation of the extrastriate visual and parietal areas during tasks associated with the sense of touch. However, there is contradictory evidence regarding the activation of the striate cortex (also known as the primary visual cortex) during the same task. In Buchel's PET study (1998), different activation patterns in the visual cortex were found in people with late-onset blindness compared to those with congenital blindness. People with late-onset blindness showed significant activation in the primary visual cortex. However, people who had no vision since birth did not show activation in the primary visual cortex. In contrast, Sadato's PET study (1996) showed activation of the primary visual cortex in both those with late-onset and congenital blindness. Many PET and fMRI studies have generated contradictory views in regards to the different activity patterns.

This research will take a different approach on this issue by employing a mental model. First, visual images stored in long-term memory can contribute to the development of a mental model (see Figure 29). People with late-onset blindness typically retain visual experiences from early life, which leads to the promotion of the activation of primary visual cortex. However, the construction of a mental model is also influenced by information from other channels, such as the sense of touch, particularly in people with visual impairment (see Figure 30). Human mental models are complex and incorporate all relevant information associated with the temporal, spatial, causal, and person- and object-related features of a particular event (Noordzij et al., 2006). Despite being blind from birth, a person can possess certain experiences related to the sense of touch throughout their life. Such an experience can be induced by previous tactile exploration of, for example, a toy or through descriptions provided by family, friends, or the media (Sadato et al., 1996). Spatial imagery based on the sense of touch can emerge even in people with congenital blindness (Sadato et al., 1996). Consequently, it follows that preserved perceptive experiences also contribute to the construction of visuospatial mental imagery even in those blind from birth. This explains why activation of the primary visual cortex also occurs in people with congenital blindness. In summary, brain plasticity in the primary visual area depends not only on preserved visual experiences, but also on touch-based experiences. Based on this logic, this research suggests that different levels of visual experience and touch-based experiences result in different degrees of brain plasticity, which in turn, causes various behaviors and levels of performances in people who have congenital, early-, and late-onset blindness.

2.9.6. People with residual vision

Previous studies have only focused on those with total blindness or intact vision, rather than those with residual vision (e.g., with severe and moderate visual impairments). Very few studies have considered the relationships among residual vision, performance, and behaviors. Those with residual vision should be further investigated. It is quite often observed that people with residual vision prefer using their residual vision in everyday life, despite its limitations. In a recent study (Plimmer et al., 2008), students with residual vision attempted to get their eyes very close to the chalkboard (or whatever the contents were presented on) and read contents by using their residual vision, as well as the sense of touch. Additionally, older adults with AMD tended to rely on their residual vision (Carbonell et al., 2003). Clearly, those with residual vision take advantage of what vision they do have. One would expect that brain plasticity also occurs in these cases to compensate for the loss of visual sensory input, although they did not lose all of their sight. As shown in Figure 32, vision is also one of the routes that facilitates mental model construction. People with total blindness cannot use this vision route. People with intact vision can use visual trace and visuospatial mental images, but cannot take advantage of the brain plasticity that serves to enhance haptic capability. In addition to sighted people, those with residual vision can also rely on both visual trace and visuospatial mental images. However, those with residual vision are influenced by brain plasticity because of their partially impaired vision, and their enhanced haptic capability. Therefore, this research suggests that the mental models of people with residual vision will be different from those with total blindness or intact vision, which in turn, will differentially influence their behaviors and performance related to the sense of touch. To this author’s knowledge, and based on an extensive literature review, there has been very little research on this issue.

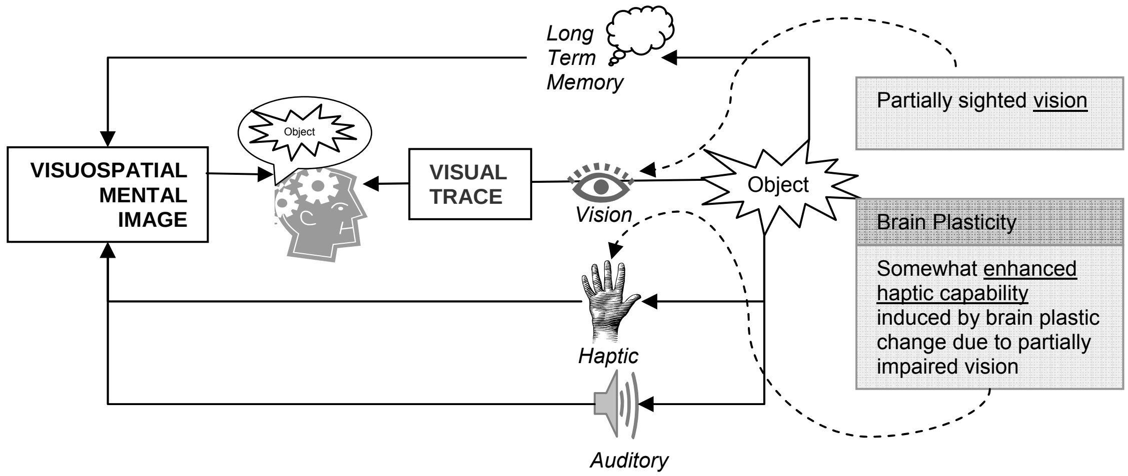


Figure 32. People with residual vision can rely on both routes: vision and haptic

In summary, this research began with a discussion of the phenomenon that people who fall into the same category of disability, such as visual impairment, generally perform the same task related to the sense of touch differently and produce diverse outcomes. Empirical studies, for instance, showed that participants with congenital, early-, and late-onset blindness performed the same task, such as a length estimation task, mental representation of the spatial displacement of a spot, and a mental rotation task, differently. To gain a better understanding of such differences in people with various visual impairments, this research first explored how human beings interact with the world, which led to a discussion of the two distinct views on human's perception: the ecological approach (also referred to as Gibson's direct perception theory) and mental models (also referred to as Gregory's indirect perception theory). In a review of the relevant theoretical and empirical literature, it was shown that people with visual impairment rely on an indirect, top-down, and interpretive approach, which is consistent with the indirect perception theory (i.e., mental models). In addition, it was evidenced that many usability studies have taken advantage of the concept of mental models in designing products. The research then raised the question as to whether those with visual impairments have the same mental model of the real world as those with no visual impairment. In short, people with visual impairment have different mental models than people with sight. People with blindness, for instance, interact with the world though a certain mental model that is constructed from different sources (e.g., long-term memory, auditory modality, and haptic modality), which can be factors, in turn, that influence their behaviors in response to the world. According to brain plasticity theory, brain cortical reorganizations occur in individuals who have impaired sensory modality, such as visual impairment, to compensate for their handicaps, which ultimately leads to enhanced capability in the remaining modalities. Furthermore, neuroscience studies have empirically demonstrated that age of onset of vision loss influenced the degree of brain plasticity and abilities in the remaining modalities. In fact, a large number of previous studies involved participants with total blindness or intact sight rather than those with residual vision. Very few studies have considered the relationship between visional impairment and performance. This literature review indicates that there is a need for further investigation of people with residual vision. As shown in Figure 32, vision is one of the crucial routes facilitating mental model construction. In contrast to sighted people, those with residual vision can continue to take advantage of the visual and tactile modalities enhanced by brain plasticity. This research therefore suggests that their residual vision and an enhanced touch sensation differentially influences their mental models compared to sighted people. Consequently, individuals with residual vision are more likely to possess different performances (haptic capability) and behaviors (interactions with haptic user interfaces) compared to those with intact sight (see Figure 33).

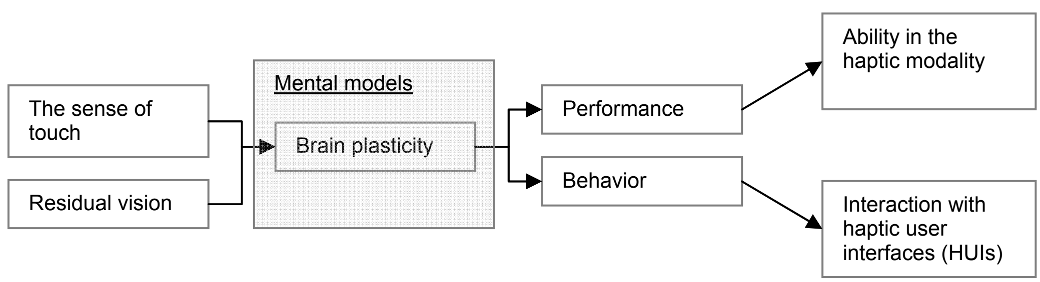


Figure 33. Two primary themes (i.e., capability in the haptic modality and preferences for HUIs) in this research

2.9.7. Older and younger individuals with residual vision

Although both younger and older people with residual vision are placed in the same disability category, older adults also experience age-related sensory degeneration. In particular, changes occur in the sense of touch, which leads to limited haptic sensory inputs. According to the mechanism of brain plasticity, such as deficient sensory input is more likely to affect one's brain plasticity, which would ultimately influence one's performance and behavior (see Figure 34). Thus, it is anticipated that the performance and behaviors of older people with residual vision will be different from that of their younger counterparts with residual vision.

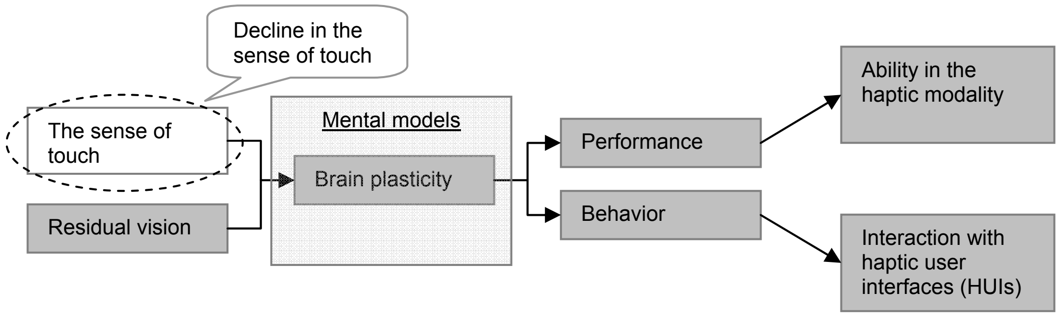


Figure 34. Elderly people with residual vision show declines in the sense of touch compared to their younger counterparts

Sensory tests (e.g., threshold methods) often show differences between younger and older individuals. Threshold methods are used to determine one's strength or the concentration of a given stimulus required to produce a minimal detectable effect (detection threshold), recognizable effect (recognition threshold), or change in effect (difference threshold) (Chambers IV & Wolf, 1996). For instance, the vibrotactile thresholds detection test (Goble, Collins, & Cholewiak, 1996) was conducted in younger (aged 18-33 years, mean = 22 years) and older (aged 57-78 years, mean = 67 years) individuals. After participants were instructed to hold a contactor, a 10 Hz stimulus was initially presented in 5-ms bursts in durations at 2-s intervals. Participants were then presented with 10 blocks of 30 trials that consisted of 10 sinusoidal frequencies (10, 25, 50, 80, 120, 160, 200, 250, 320, and 400 Hz). The results showed that the sensitivity of older participants was significantly worse than in their younger counterparts. The threshold difference between the two groups was 10 dB on average (ranged from 8 dB to 12 dB). Higher thresholds were observed in older participants at all frequencies. The vibrotactile thresholds detection test leads to the conclusion that the differences were accounted for by age-related changes in receptors. A progressive decline in sensitivity with age results from physiological changes in the skin (Goble et al., 1996). Pacinian corpuscles, Meissner's corpuscles, and Merkel's disks are known receptors contributing to the detection of vibrotactile stimuli at threshold (Bolanowski, Gescheider, Verrillo, & Checkosky, 1998). Goble et al. (1996) showed that the number of Parcinian and Meissner's corpuscles gradually decreases with age.

In addition, Kenshalo (1986) explored tactile absolute thresholds with age. Absolute thresholds to cutaneous stimulation in younger (aged 19-31 years) and older (aged 55-84 years) participants were compared in two areas of the body: (1) the palm of the hand just beneath the thumb (also referred to as the thenar eminence), and (2) the bottom of the foot (referred to as the plantar foot). The cutaneous stimulation included, for example, single ramp-and-hold skin indentations at 1 mm/s (3 to 170 μm and 63 to 1640 μm), and vibrations (sine waves of 40 and 250 Hz). The results showed that older participants were significantly less sensitive to mechanical stimuli (tactile and vibration) in both areas compared to their younger counterparts.

Considering the evidence showing the different capabilities relevant to the sense of touch, it can be concluded that older adults are vulnerable not only to age-related visual impairments, but also age-related touch impairments. As a result, the deficit sensory inputs from the sense of touch would influence brain plasticity in elderly individuals with residual vision in a different way than their younger counterparts with residual vision. Ultimately, it would lead to different performances (i.e., capabilities in the haptic modality) and behaviors (i.e., interactions with HUIs).

2.9.8. Two aspects of people with residual vision

What has been discussed so far has led to the contention that people who retain residual vision are influenced by brain plasticity differently than people with total blindness or those with intact vision. Consequently, it is anticipated that people with residual vision will show distinct differences in (1) performance (i.e., capabilities in the haptic modality), and (2) behaviors (i.e., interactions with HUIs). In the following sections, the assessment techniques for capabilities in the haptic modality and interactions with HUIs will be explored.

2.9.9. Magnitude estimation technique to measure haptic capability

Ideally, brain-imaging technology (e.g., fMRI, PET) is used to facilitate the understanding of the relationships between specific cortices of the brain and the function they serve when people with residual vision perform a specific task related to the sense of touch. Such brain imaging technologies aim to measure brain function by the measurement of brain oxygen consumption, blood flow, and glucose metabolism (Martin, 2006). Unfortunately, medical schools generally possess imaging technology-related equipment and facilities. Additionally, equipment is quite expensive. For example, a new 3.0 Tesla scanner costs between $2,000,000 and $2,300,000. This lack of accessibility is likely to limit this research.

Today, imaging technology contributes to an understanding of the brain's activity, structure, and function; however, it is difficult to believe that imaging technology is the only way to study the brain. Recent neuroscience studies encountered challenges associated with the effectiveness of imaging technology. In fact, the term 'deactivation' in brain imaging technology does not necessarily imply that the deactivated areas are not involved in the task. In fact, the underlying assumption of these brain studies is that the brain images are areas of increased blood flow caused by enhanced neural activity during cognitive efforts (Martin, 2006). However, this assumption is not always valid. For example, brain activity in specific cortices appears to be active during learning, but typically there is also a decrease in activation in those same cortices when one becomes an expert (Martin, 2006). Novel stimuli generate activation, but repeating stimuli typically leads to a decrease in neural activity (Yi, Kelley, Marois, & Chun, 2006).

Alternatively, a magnitude estimation technique can be used to measure the extent to which the sense of touch is enhanced in people with residual vision (see Figure 35). A large number of disciplines have contributed to the understanding of the human brain. Psychologists, psychiatrists, radiologists, pharmacologists, physiologists, and biochemists have used their background knowledge and techniques that overlap across different disciplines. For example, if a participant performs poorly at a task that is normally performed poorly by someone with brain damage, further examination using fMRI or PET to directly examine the brain might be recommended. This procedure also works the other way around (Martin, 2006); in other words, if a certain area of the brain is damaged, it might be recommended that a patient be tested to investigate deficits in their performance or capabilities. In short, the use of imaging technology can be linked to direct assessment, whereas the use of performance tests is linked to indirect assessment. Both types of assessment contribute to the study of the brain. As a type of indirect assessment, the magnitude estimation method can be employed in this research. Magnitude estimation is a psychophysical ratio scaling technique in which an observer (or an assessor) is required to make numerical estimations of the sensory magnitudes generated by various stimuli (Gescheider, 1997). Ultimately, this technique enables an investigator to understand a participant's sensitivity related to the sense of touch. For example, Jednorog and Grabowska (2008) adopted the magnitude estimation technique when measuring the touch sensitivity of Braille readers with visual impairments. A set of 12 cylindrical rods were covered with different grades of sandpaper, which were glued to their curved surfaces. Each participant was randomly given a set of two rods and instructed to distinguish whether the surfaces of the two rods were the same. Jednorog's study simplified the magnitude estimation technique in that the criteria for assessing stimuli discrimination were determined by only two types of participants' answers: "*Yes, it is the same*" or "*No, it is different.*" Data produced by the magnitude estimation technique is indeed analyzed in a more systematic way.

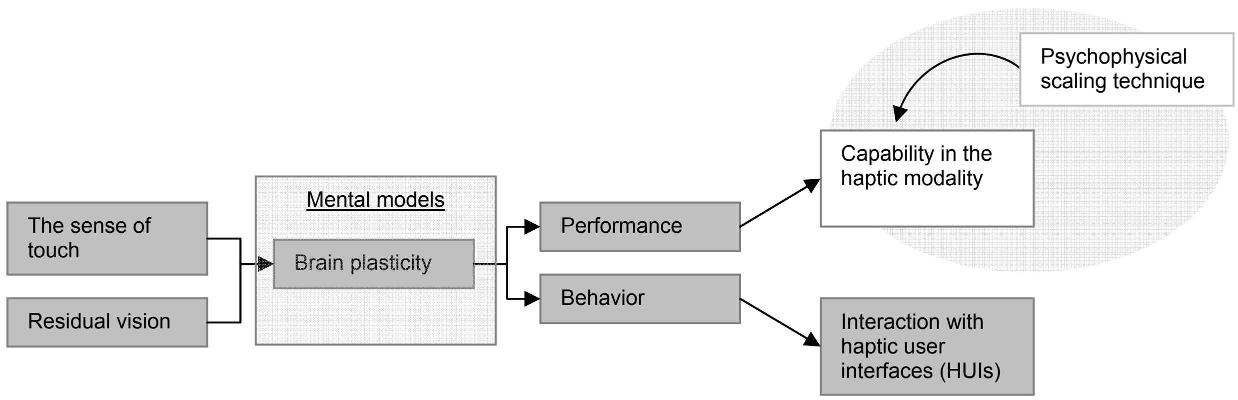


Figure 35. A psychophysical scaling technique is used to measure sensitivity relevant to touch

More specifically, the magnitude estimation technique is based on Steven's law, which states that the magnitude of the perceived intensity is related to the magnitude of the physical stimulus raised to a power (Schiffman, 2000). This is called Steven's power law, which is often described as the equation,

$$\psi = kS^n$$

where ψ is sensation, ***k*** is a constant, ***S*** is stimulus intensity, and ***n*** is the exponent to which the intensity is raised (Stevens, 1957). There are two aspects related to the exponent, *n*: (1) the exponent implies the relationship between the magnitudes of the perceived intensity and the physical stimulus, and (2) a unique value is assigned to the exponent for each sensory dimension (e.g., brightness, loudness, and tactual roughness). Stevens provided representative exponents, *n*, for various sensory dimensions (Schiffman, 2000). For example, when the magnitude estimation method is used for the estimation of roughness, the exponent of the power equation is 1.5 and the equation becomes $\psi = kS^{1.5}$. The relationship between the magnitude of the perceived intensity and magnitude of the physical stimulus can also be illustrated by plotting a curve called a power function, where the x-axis is the magnitude of the physical stimulus and the y-axis is the magnitude of the perceived intensity. The exponent, n, serves to shape the power function's degree of curvature (i.e., slope) and to indicate how the magnitude of the perceived intensity increases in response to the magnitude of the physical stimulus. When magnitudes of perceived intensity and physical stimulus are converted and plotted on logarithmic scales, it is easier to identify their relationship; in other words, instead of the curvature of the functions, the power function is presented as a straight line.

When conducting the magnitude estimation at a practical level, an assessor is first presented with a standard stimulus and is informed that its sensation has a certain, predefined numerical value. Different levels of stimuli are subsequently presented and the assessor is instructed to judge one by one how many times greater one sensation is over another (especially the first one). In other words, the estimation is based on the ratio between the first stimulus and the others. Analysis of haptic perception is often conducted by a physical measurement of roughness (Bergmann Tiest & Kappers, 2006c). In addition, the roughness perception is typically measured by using sandpaper stimuli (Bergmann Tiest et al., 2007; Diamond et al., 2001; Verrillo et al., 1999). Consequently, the haptic perception of participants in the present research can be investigated using the roughness test with sandpaper. For instance, if the first stimulus (e.g., a piece of sandpaper's toughness) is initially assigned a value of 10 and a subsequent stimulus (e.g., another piece of sandpaper's toughness) seems twice as rough as the first stimulus, a value of 20 would be assigned to the second stimulus, as shown in Figure 36. The predefined, standard stimulus is also called a modulus. According to ISO 11056 (ASTM, 1999), a scale should have no upper limit; however, the value 0 shall be assigned only in the exceptional case, for example, when any attribute is not perceived at all. Assessors are instructed to use round numbers such as 5, 10, and 15 in the scaling technique.

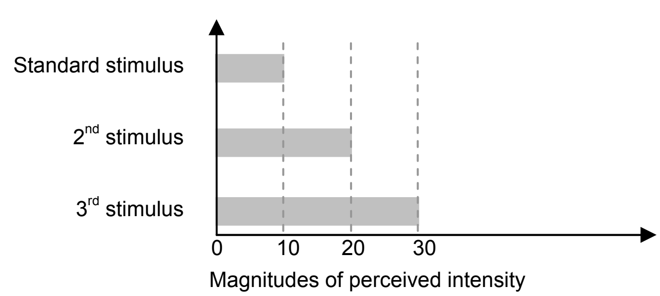


Figure 36. The first stimulus serves as a reference to estimate the magnitudes of the other stimuli

In addition to Steven's power law, there are other psychophysical scales of sensation: Weber's Law and Fechner's Law. Weber's Law asserts that the change in stimulus intensity that can be discriminated is *always* a constant fraction of the stimulus intensity (Gescheider, 1997). It can also be described as

$$\frac{\Delta\phi}{\phi} = c$$

,where $\Delta\phi$ is the difference threshold, ϕ is the initial stimulus intensity, and c is a constant fraction. Even though Weber's Law gives valuable insights into the description of the most intense discrimination data, Weber's law is inapplicable to audio intensity discrimination and tactile discrimination. The Weber fraction ($\Delta\phi / \phi$) is not constant when auditory stimuli with a frequency of 4,000 Hz and 250 Hz sinusoid of vibratory stimulation was presented near the thumb (Gescheider, 1997). On the other hand, Fechner's Law supports the notion that a sensation's magnitude is a logarithmic function of the stimulus, which is expressed as

$$\psi = k \log \phi$$

,where ψ is the sensation magnitude, ϕ is the intensity of the stimulus, and k is a constant (Gescheider, 1997). Fechner's Law's k considers the Weber fraction for a sensory dimension. A well-known assumption of Fechner's Law is that Fechner's Law is valid only when Webber's Law is correct. Given the fact that Weber's Law is not valid in certain audio and tactile intensity discrimination assessments, it was concluded that these two laws could not be applied to this research because it deals with human sensitivity to touch. Furthermore, Fechner's Law is currently not considered an accurate statement for explaining the relationship between the magnitudes of perceived intensity and physical stimulus (Gescheider, 1997). In contrast, today, it is accepted that Steven's Power Law is useful in psychophysics because it can scale almost any sensory dimension (Schiffman, 2000). The magnitude estimation technique based on Steven's Power Law is widely used in academic research, product development, and consumer surveys (Chambers IV et al., 1996).

In short, magnitude estimation based on Steven's Power Law is a psychophysical scaling technique that contributes to the calculation for how much of a given objective stimuli an individual can subjectively perceive. The magnitude estimation can be applied to this research; in other words, individuals with residual vision should be examined to investigate the extent to which they perceive the same objective stimuli differently compared to a control group, such as individuals with intact vision. In general, analysis of human haptic perception is conducted by the physical measurement of roughness (Bergmann Tiest & Kappers, 2006b). The roughness measurement is typically facilitated by using sandpaper stimuli (Bergmann Tiest et al., 2007; Diamond et al., 2001; Verrillo et al., 1999).

2.10. User needs elicitation method to study interaction with HUIs

In addition to capabilities in the haptic modality, interactions with haptic user interfaces are also influenced by brain plasticity. As discussed earlier, the brain of those who retain partial sight attempts to compensate for the visual sensory loss by altering brain structure. However, they can continue to use their vision, unlike people with total blindness, and they take advantage of brain plasticity, unlike those with intact vision. In other words, people with residual vision can utilize all information from both visual trace and visuospatial mental images while constructing mental models of the world. As a result, these conditions would differentially affect their mental models compared to their counterparts who are blind or have intact vision, which ultimately influences the performance and behavior of people with residual vision. In the previous chapter, the measurement of their performance (i.e., capability in the haptic modality) was discussed; the following chapter is devoted to the assessment of their behavior (i.e., interaction with haptic user interfaces). Because those with residual vision have different capabilities related to the sense of haptic, it is postulated that they deal with haptic interfaces differently and require different user interface designs. Thus, there is a need to investigate how they deal differently with haptic user interfaces; in other words, a user needs assessment is required (see Figure 37).

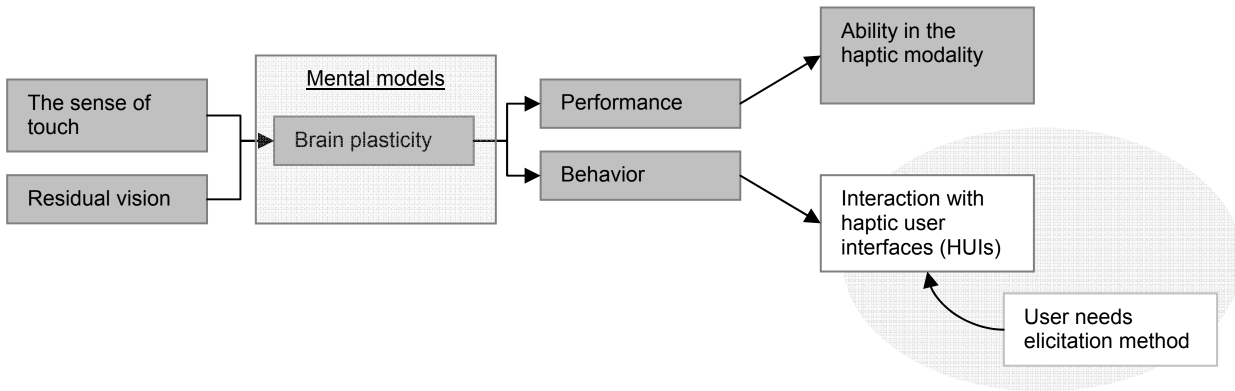


Figure 37. A user needs elicitation method is used to explore the interaction with HUIs

However, more importantly, in order to investigate how users differently interact with HUIs and what types of interfaces users want, we first need to investigate whether today's design approaches are applicable to such design contexts as users with visual impairment and non-graphical user interfaces. The following chapters are devoted to a literature review of today's design approaches, including haptic user interfaces, for users with disabilities, particularly visual impairments.

2.10.1. User involvement

In existing design contexts, users with disabilities are less likely to get deeply involved in design activities. In fact, there is no doubt that numerous studies have made enormous efforts to improve the accessibility of users who have disabilities. However, accessibility evaluations were often performed with users who had no disability, and the resultant data or design ideas were then extrapolated to users with disabilities (Abascal, 2002). In the early design phase, an assumption was often made that both users with visual impairments and those with intact vision have equivalent cognitive profiles (Stevens et al., 1997). A large number of HCI studies also paid less attention to the analysis of user needs in the pre-design phase, especially in dealing with users with disabilities (Abascal, 2002; Abascal & Azevedo, 2007). Consequently, designers merely relied on their own mental model and knowledge during design development. Such a presumptive design approach fails to reflect user needs adequately, which ultimately causes user dissatisfaction and abandonment. In general, designers who have no disability cannot or can hardly imagine what users with disabilities experience to cope with their handicaps in everyday life, as well as what they want (Wu, Baecker, & Richards, 2005). When people with disabilities were allowed to make a decision on certain issues, they were often very different from those decisions made on their behalf (Mason, 1992). Based on all of the evidence stated earlier, there is a high likelihood that users' preferences are not represented accurately. Users with disabilities know how to design assistive technology applications better than designers without disabilities do. Thus, users with disabilities should be involved throughout the entire design process.

Furthermore, even some previous studies that included users with disabilities in design development were merely focused on a summative evaluation. Very few paid attention to eliciting user needs in the early design phase (Luck, 2003). After designers make a decision on the final version of a prototype, users with disabilities are then invited to provide feedback on the prototype in the late design phase (Edwards, 1989; Holman et al., 2007; Kerr, 1983; Plimmer et al., 2008; Sapp, 2007; Stevens et al., 1997). Development of a system for individuals with disabilities should be achieved by involving the intended users (i.e., individuals with disabilities) in the entire development process.

In this regard, a participatory design approach can contribute to user involvement throughout the design development process. Participatory design assigns users as co-designers and also empowers them to become deeply involved in the design process (Buhler, 2001; Coleman et al., 2004; Lindgaard et al., 2001). The participatory design approach has been shown appropriate and effective for people with disabilities (Wattenberg, 2005; Wu et al., 2005). For example, people with disabilities are able to obtain opportunities to express their needs rather than adopt to what others have done for them. In addition, they can think of themselves as a contributor to the enhancement of a system by providing important and valuable feedback (Wattenberg, 2005). Francis et al. (2005) pointed out that the advantage of the participatory design approach for people with autism was that the rate of technology abandonment was reduced because of the inclusion of users with autism in design development. In addition, involving elderly users in the design process and specification of requirements will enable investigators to correctly identify elderly user needs and system requirements (Dewsbury et al., 2006). Participatory design meetings can be regarded as a social event for older users. Trust and friendship are gradually built among designers and older users in the design meetings, which would facilitate communication in meetings (Masssimo & Baeker, 2006). Active communication contexts are likely to help older users articulate their needs clearly. In short, the participatory design approach emphasizes user involvement in system development and facilitates not only the enhancement of technical capabilities, but ultimately, greater acceptance and use (Robey, Farrow, & Franz, 1989). In the next section, the participatory design approach is discussed in further detail.

2.10.2. Various approaches to participatory design

There has been a growing movement such that design activities have shifted from a user-centered design to a participatory design. The primary goal of a user-centered design is to focus on the design '*for' users*. On the other hand, a participatory design aims to accomplish the design '*with' users*. A user-centered design typically emphasizes the design artifact per se to ensure that it meets user needs (Sanders, 2002). However, a user-centered design excludes users in most design processes. On the contrary, a participatory design views intended users as a critical component in the design process (Sanders, 2002). A participatory design approach supports the notion that each individual has valuable ideas contributing to the design, and users should be allowed to participate in the entire design process to express their needs directly.

A participatory design approach was developed by researchers from Scandinavia in the 1970s and 1980s (Torpel, 2005). A participatory design approach originally emerged from political contexts especially related to the Scandinavian workplace democracy movement (Muller, 2003). It was meant to balance the power of management and labor in the development of computer systems in the workplace (Spinuzzi, 2000). For example, a concept of partnership was generated to allow workers to make a decision on new technologies that would be introduced in their workplaces. A participatory design focused on allowing users to have equivalent power in designing artifacts for their own use (Spinuzzi, 2000).

Various approaches to the participatory design have emerged. The approaches include an ethnographic field method (Blomberg, 1993), cooperative design (Bodker et al., 1993), contextual design (Beyer et al., 1998), and PICTIVE (Muller, 1991; Muller, 1993). Although the four approaches are under the same umbrella of a participatory design, they are slightly different in terms of the prototyping technique, user involvement in the development of initial prototypes, partnership (or user empowerment), time to accomplish, required number of participants, purpose of prototypes, communication, and identification of users' goals. The four design approaches are compared across these eight aspects, and are summarized in Table 8.

Table 8. A comparison of different approaches to participatory design

approaches / attributes	Ethnographic field method	Cooperative design	Contextual design	PICTIVE
1. Prototyping techniques	Limited use of prototypes	High-fidelity prototype	Low-fidelity prototype	Low-fidelity prototype
2. User involvement in the development of initial prototypes	Limited use of prototypes	Initial prototypes already developed by designers	Initial prototypes already developed by designers	Initial prototypes are prepared by both designers and users
3. Partnership (user empowerment)	Weak partnership	Weak partnership	Weak partnership	Strong partnership
4. Time	Long (a minimum of six months to a year)	Long (several weeks)	Long	Relatively short
5. Number of participants	Large sample	Large sample	Large sample	Small sample
6. Use of prototypes	Limited use of prototypes	Evaluation of design (investigation of breakdowns)	Evaluation of design (observation of user reaction)	Creation of design
7. Communication with users	Combination of direct and indirect ways (informal interview, observation, and video recording)	Direct ways (a face-to-face dialogue, same time, same place)	Direct ways (a face-to-face dialogue, same time, same place)	Direct ways (a face-to-face dialogue, same time, same place)
8. Freedom to operate a prototype by fulfilling a user's goals/intentions during design activities	Limited use of prototypes	Free to operate (e.g., trials of a prototype in a work-like situation over weeks without a given task to complete)	Free to operate (e.g., trials of a prototype at users' worksites without a given task to complete)	Free to operate (e.g., strong partnership that enables users as co-designers to design a prototype)

2.10.2.1. Ethnographic field methods

Ethnography is an approach to understand the culture of a social group in terms of the tacit rules, practices, and conventions (Spinuzzi, 2000). Although ethnography was originally not intended to facilitate a design activity (Spinuzzi, 2000), numerous researchers have adopted and taken advantage of it to design a variety of HCI artifacts (Bentley et al., 1992; Blomberg, Burrell, & Guest, 2003; Nardi, 1993). Ethnographic field methods focus on understanding the users' behavior in everyday contexts, which in turn, helps designers to design HCI artifacts that accommodate the needs of users. Consequently, designers spend more time on testing and evaluating features of the design to satisfy users' needs (Blomberg, 1993).

An ethnographic study is generally accomplished with a large number of users over a long period. Designers spend a minimum of six months up to a year attending meetings, watching group members' work, distributing questionnaires, and conducting informal interviews (Dohenny-Farina & Odell, 1985; Spinuzzi, 2000). In particular, the observation of ongoing activities in the target group is regarded as important to a successful ethnographic study (Blomberg, 1993). Designs based on ethnography are not meant to develop a prototype. Instead, designers focus on naturally occurring phenomena in a target group's social contexts. A large number of group members are essentially included in the ethnographic study.

In addition, the degree to which users are empowered is relatively low compared to other design approaches. Designers generally visit and participate in the users' world. The designers communicate with users indirectly by observing users' activities, asking follow-up questions, or recording a video. After the observation or interview, designers interpret and assign meanings to users' activities (Blomberg, 1993). Although users' performances and self-reports appear to play a central role in data collection, design solutions are decided by designers based on the ethnographic data (e.g., observation, interview, or designers' participation) (Blomberg, 1993). In addition, there is a high risk that the focus of an ethnographic study will be biased by fieldworkers or designers. Because they view the users' work domain through their own eyes, they tend to see only the side in which they are interested. Consequently, users' goals and intentions are less likely to be revealed. Unfortunately, there are limited partnerships between designers and users in the ethnographic method.

2.10.2.2. Cooperative design

In the first decades of computer system development, users were excluded in design development. In fact, computer systems were typically used by developers (e.g., engineers and programmers) at that time (Bodker & Gronbaek, 1991; Gronbaek, Grudin, & Bannon, 1993). Thus, user involvement in design development was unnecessary. In other words, involving only the developers was good enough. However, when the rate of computer technology penetration in work environments became significantly higher

(Gronbaek et al., 1993), cooperative development contexts (i.e., inclusion of users) was seriously considered in system design processes (Bodker et al., 1993). Cooperative design is intended to be accomplished through collaboration between users and designers, instead of designers' working solo to develop user requirements (Spinuzzi, 2002).

High-fidelity prototyping techniques are normally employed in the cooperative design approach. Unlike mock-ups, a cooperative prototyping technique is applied exclusively to computer applications (Spinuzzi, 2002). The cooperative design is often carried out by the use of computer applications, which is referred to as the high-fidelity prototyping technique.

However, the cooperative design approach partially permits user involvement in developing a prototype. To encourage users to actively participate in the design process, designers typically allow users to experience a prototype in a simulated future work situation (Bodker et al., 1991). When breakdowns occur during the use of the prototype, users and designers collaborate to find the problem and solution to improve designs. An initial prototype is typically prepared in advance (Bodker et al., 1993). However, only certain people such as researchers, designers, or developers are invited in the decision-making process on how to shape an initial prototype (Bodker et al., 1993). Users are excluded from the decision-making process.

The cooperative design approach serves to ensure equal partnership between users and designers; however, the partnership becomes weakened in dealing with prototypes. Users in the cooperative design approach view the design activity as secondary work, while designers consider it their primary work (Bodker et al., 1993). This means that designers must do more homework to prepare the prototyping procedures by making decisions, for example, on the degree to which a prototype is stable and the degree to which a prototype is modified (Bodker et al., 1991). Therefore, developers have more opportunities to contribute to the decision-making process than users, although users are allowed to participate in design development for some period.

The cooperative design is conducted in four design phases over several weeks including approximately thirty users (Bodker et al., 1993). The first step is to explore users' work. Four to five researchers visit the worksite for several days. The second step emphasizes the problems and ideas that the target users have, and is called a future workshop. Two and one half hours are assigned to the future workshop, which is run by at least two facilitators and 20 users. Organizational games, the third step, are accomplished by 10 to 20 users over 2½ days. The final step is to illustrate ideas by means of a mock-up and cooperative prototyping. Additionally, users are instructed to try the prototype in work-like situations over several weeks.

A prototype is used to facilitate an evaluation of its design. As discussed earlier, when a breakdown occurs in users operating a prototype, both users and designers work together to analyze the situation. A prototype is immediately modified by communication between designers and users. Since users are allowed to freely explore the prototype, users are able to investigate whether their own goals fit the prototype, unlike other usability studies, which only allow users to perform certain given tasks (Norman, 2004). For example, users in the cooperative design are able to browse Web sites in a random manner depending on users' goals. The cooperative design supports a way of knowing the user's goals.

2.10.2.3. Contextual design

Contextual design, developed by Hugh Beyer and Karen Holtzblatt (1998), is accomplished by gathering data, driving design, and managing the organizational context. In the contextual design approach, designers typically attempt to understand users by asking questions while users are working at their worksites, which is referred to as a contextual inquiry (Beyer et al., 1998; Kensing & Blomberg, 1998). The contextual inquiry is based on a field methodology approach in which designers participate in the user's world (Beyer et al., 1998).

A low-fidelity prototyping technique, such as the paper prototyping technique, is employed to model work practice and user interface designs (Bodker et al., 1993). For example, participants use sticky notes as pull-down menus, buttons, and other objects in the interface (Beyer et al., 1998). Thus, low-fidelity prototypes help participants easily understand the target system in the design phases. Additionally, the use of low-fidelity prototyping techniques is an efficient way to (1) explore the design aspects, (2) predict user preferences in the actual product, (3) enhance user participation in the design process, (4) visualize possible design solutions, and (5) provoke innovation (Virzi, Sokolov, & Karis, 1996).

Initial prototypes are often built without user involvement. After prototypes are created, designers typically show these prototypes to users and conduct a contextual inquiry by observing users' reactions

(Muller, 1993). Users are also allowed to alter the work model or user interface design directly; however, their access to initial prototype development is limited.

The degree to which users are empowered in contextual design tends to be limited. An affinity diagram method is carried out to analyze data from the contextual inquiry (e.g., observations, walkthroughs, and interviews) in terms of physical environment, workflow, sequence, and artifacts. The contextual inquiry allows designers to build abstract models of underlying work structures (Beyer et al., 1998; Spinuzzi, 2000). Design solutions are developed from work models that are built by designers instead of users (Spinuzzi, 2000). Although users are referred to as co-designers, and allowed to participate in design activities, they are prohibited from contributing to the work model. Contextual inquiry is not suitable if users are to have equal power in the entire design process.

A contextual design team sends three to five individuals (e.g., researchers, investigators) to a user's worksite to conduct a contextual inquiry. In addition to the contextual inquiry, a paper prototype is also employed to allow users to input their opinions in the work model or user interface designs. Specifically, the contextual inquiry involves one-on-one interactions (e.g., face-to-face dialog) between the interviewers and interviewees that lasts two to three hours (Beyer et al., 1998). The design team makes return visits afterward. Consequently, the time required to accomplish contextual design depends on how many interviewees are included. According to Holtzblatt et al. (1993), designers conducting contextual design can never guarantee that they talk with a sufficient number of users to ensure completeness for a target population. Given the fact that contextual inquiry is originally rooted in ethnography (Spinuzzi, 2000), a large number of participants must be involved for a successful contextual design.

In addition, interview questions in a contextual inquiry are typically developed by designers. Designers might see only one side of an issue that they are interested. Consequently, the contextual design approach is greatly influenced by designers who pursue their own design goals and their own interests regardless of users' perspectives.

<u>2.10.2.4. PICTIVE</u>

PICTIVE or Plastic Interface for Collaborative Technology Initiatives Video Exploration is one of the participatory design approaches, and relies on a combination of low-tech (i.e., low-fidelity prototype) and high-tech (i.e., video camera) (see Figure 38). The low-fidelity prototyping technique incorporates simple office supplies (e.g., paper-and-pencil, Post-it notes). Since simple office supplies are used, it is easier for users to understand the prototypes and visualize the target systems. The “plastic” in PICTIVE implies three characteristics: composition, ease of change, and artificiality (Muller, 1991). More specifically, participants using PICTIVE are able to modify the plastic components of the prototype quickly and easily. A set of colored plastic items contributes to its durability and inexpensiveness. A camcorder is used to record the design activities on the shared design surface, which in turn, provides a set of data for analysis, issue exploration, and design guidelines. Certain prototyping techniques implement software applications, which sometimes makes participants confused about technical feasibility because participants do not understand why a working prototype represented by a high-fidelity prototype is not quickly transferred into a release-version system. In contrast with these prototyping techniques, PICTIVE is based on plastic items so that participants are fully aware of its artificiality.

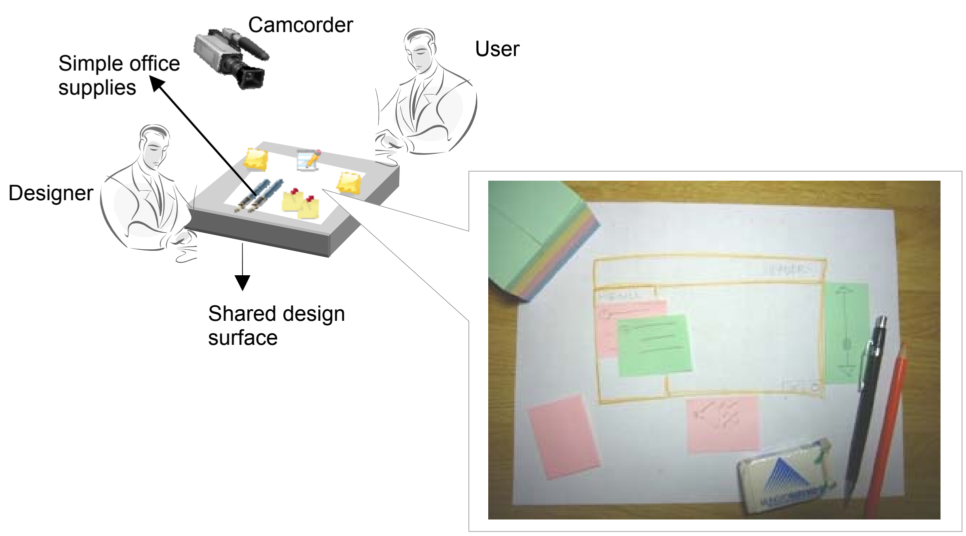


Figure 38. Visualized PICTIVE session

Users are equally empowered to contribute to design activities as co-designers (Muller, 1991). For example, even the initial prototype is developed and modified by both designers and users. Additionally, PICTIVE has users involved in the whole design process and also allows them to influence the design decision-making process (Muller, Wildman, & White, 1993).

Unlike an ethnographic field study, PICTIVE does not require a long time to complete design activities. In contrast with contextual design, PICTIVE does not require repeated visits to participants. In addition, PICTIVE does not involve a large group of participants. Muller et al. noted that PICTIVE is a small group exercise (Muller, Wildman, & White, 1994). Design solutions are typically driven by synthesizing participants' different views (Muller, 1993).

Prototypes serve to 'create' user interfaces rather than 'evaluate' already-designed (or developed) user interfaces. Although a contextual design also relies on a low-fidelity prototyping technique by means of paper prototypes, it does not focus on supporting users to create HCI artifacts. Rather, contextual design supports users in analyzing developers' ideas by allowing users to modify the already-designed user interfaces. While users and designers collaborate by creating HCI artifacts, they are permitted to communicate directly in face-to-face dialog in the same place at the same time. Since users are allowed to control design activities with equal power, they are able to obtain opportunities to fulfill their goals while designing the target system.

2.10.3. Implications for this research

In the previous section, four different design approaches to the participatory design were compared. Various aspects of these design approaches were discussed, including prototyping techniques, user involvement in the development of initial prototypes, partnerships (or user empowerment), time, number of participants, purpose of prototypes, communication, and freedom to operate a prototype by fulfilling a user's goals/intentions during design activities. The review revealed that each design approach has strengths and weaknesses. However, overall, PICTIVE shows multiple benefits over the other design approaches.

First, strong partnerships between designers and users lead to more chances for users to influence the design decision-making process throughout the entire design process, including the development of initial prototypes. In addition, strong partnerships enable users to be equally empowered to have control over the design activities, and they are able to test a given prototype independently and thus satisfy their goals or intentions. Furthermore, users are allowed to have direct communication with designers in real time. Users, for example, can express their thoughts by using additional cues, such as hand gestures, facial expressions, tone of voice, and mutual responses. A prototype can serve as a way to 'create' HCI artifacts to facilitate user's design activities rather than just providing an 'evaluation.' A designer is able to understand user needs more accurately by using a prototype early in the design phase. The use of low-fidelity prototyping techniques can help participants understand complex system features. In general, accessibility and usability studies are challenged because it is often difficult to find sufficient participants with a given disability. Thus, any method requiring a large number of participants is unsuitable. In this regard, PICTIVE is appropriate because it does not require a large number of participants. In addition, PICTIVE does not require users to participate multiple times over a long period.

However, there is concern as to whether PICTIVE is applicable, particularly when designing haptic user interfaces. Kensing and Blomberg (1998) provided guidance on participatory design; ideally, a participatory design approach should facilitate users' involvement in design decision-making processes, and provide users the opportunity to take an independent position on any decision related to design solutions. Designing haptic user interfaces generates a variety of design challenges. The following sections will be devoted to discussions on the design challenges relevant to haptic user interfaces and how PICTIVE would fair given these challenges.

2.10.3.1. Design challenges for haptic user interfaces and PICTIVE

First, it is difficult to comprehensively understand haptic technology because haptic sensation and perception are relatively new in the user interface design domain. In all likelihood, few new designers have solid knowledge or experiences with haptic application design. As co-designers alongside designers, users are similarly challenged. Despite the difficulty understanding haptics, a surprising number of prior studies on haptic assistive technology have relied on high-fidelity prototypes for those with visual impairment, such as PHANToM (Brewster, 2002; Douglas et al., 2007; Liffick, 2003; Sjostrom et al., 2003; Yu et al., 2003), the Logitech Wingman force-feedback mouse (Kuber, Yu, & McAllister, 2007), Immersion's FEELit mouse (Sjostrom, 2001a), the audio-haptic browser (Roth et al., 2000b), and haptic system design software (e.g., Immersion Studio®) (Kuber et al., 2007). The high-fidelity prototyping technique often requires users to operate the final version of haptic-embedded applications directly (or already commercialized products) such as PHANToM™. Clearly, users face the challenge of understanding haptics and properly handling the prototypes. Consequently, users are less likely to generate design ideas. Users might feel uncomfortable with their role in design process, which might lead to unwillingness to participate in the design decision-making process. In general, design decision-making does not occur at only one point in time (Rouse, 1987). Many individuals with different backgrounds and individual needs are typically engaged in design processes and might make judgments and choices accordingly, which ultimately affects the system design. A typical analytical approach to design is to (1) formulate problems, (2) generate alternative solutions, (3) evaluate alternatives, and (4) select one among the many alternatives (Klein, 1987). Design decision-making is regarded as ‘ubiquitous’, which implies that decisions emerge as a result of ongoing interactions of a variety of people throughout the design process (Rouse, 1987). A lack of understanding of the nature of a target system is likely to influence one’s judgments and choices negatively, which eventually results in the failure of decision support and system design. Furthermore, Kuber et al. (2007) claimed recently that there are only a small number of words available to describe haptics correctly. Users might struggle to understand the haptic system despite expert designers’ explanations. As a result, users’ contributions to the design might be minimal, which makes it difficult to claim successful participatory design in terms of *participation in decision-making*.

Second, there is less opportunity for users to take an independent position on a problem. Since users face difficulty in gaining solid understanding of haptic technology, they presumably become more dependent on designers who have solid knowledge, which might make users remain silent and merely follow the designers’ opinions or advice. This is inconsistent with the requirements of successful participatory design; namely, *the possibility of taking an independent position on a design issue*.

However, PICTIVE is an ideal candidate for successful participatory design for haptic technology. In fact, PICTIVE is primarily achieved by a combination of low-tech prototypes and video recording devices. The low-tech prototypes are comprised of simple office supplies, such as paper-and-pencil, Post-it notes, and plastic icons. These lower-tech prototypes provide all participants with equal opportunity for access to the prototyping technology (Muller, 1993). Because simple office supplies are used, it is easier for users to understand the prototypes and future target system features. Consequently, users’ active participation is expected in the decision-making processes of interface designs. In addition, the users no longer rely on the designer, but they remain independent with regard to design problems. Virzi et al. (1996) also considered low-fidelity prototyping techniques effective methods to predict user preferences in the actual product, to enhance user participation, to visualize possible design alternatives, and to provoke innovation. Based on this review of different design approaches in participatory design and considering the design contexts of haptic technology, the PICTIVE method can best assist in haptic user interface designs.

2.10.3.2. Design challenges for users with visual impairment

In this section, whether PICTIVE is valid for users with visual impairment is discussed. PICTIVE was originally designed to help sighted people demonstrate what they want to "see" in a future system (Muller, 1993). For example, participants in PICTIVE attempt to design graphical user interfaces (e.g., drop-down boxes, menu bars, and other icons) by using colored office supplies. Additionally, they often write down the names of interface elements on colored sticky notes. Sometimes, they assign specific meanings to each color of the office supplies. This indicates that participants' vision plays a critical role in the PICTIVE method. In fact, most other conventional design approaches, including PICTIVE, are based on vision-prototyping techniques. Participants who are visually impaired cannot take advantage of such prototyping techniques. While designers are able to see the prototypes and obtain relevant information, users who are visually impaired are unable to do so. It is ironic that unequal accessibility issues occur even during the design of assistive technology applications for people with disabilities. It is necessary to modify conventional prototyping techniques (i.e., PICTIVE) to allow participants who are visually impaired access to relevant information in design development. The need to modify methods was also recognized by other researchers (Bowman, Gabbard, & Hix, 2002; Chandrashekar, Fels, Stockman, & Benedyk, 2006; Gerber, 2002; Jones et al., 2005). For instance, Chandrashekar et al. (2006) stated that the applicability of conventional usability evaluation methods should be carefully examined for users with disabilities (see the quote below).

> "It appears that TAP [Think Aloud Protocol], in its popular form as a concurrent verbal protocol method, may not be effective for use with blind persons using a screen reader to access website. Further research is required to determine how best to modify this protocol for use with these users (Chandrashekar et al., 2006, p. 252)."

Unfortunately, most studies have only focused on the need for modified methods for emerging technology developments or for people with a special need. They have not taken into account user interface designs of haptic technology operated by users with visual impairment (Bowman et al., 2002; Chandrashekar et al., 2006; Gerber, 2002; Jones et al., 2005; Roberts & Fels, 2006). The development of a new prototyping technique that accommodates participants with visual impairment in haptic user interface designs is needed.

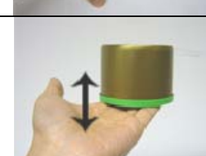
2.10.3.3. Modification of the prototyping technique in PICTIVE

In interacting with the world, the sense of touch works for people who are visually impaired as does the sense of vision for people without visual impairment. As discussed earlier, in contrast with sighted people, those with visual impairment primarily depend on other channels, such as the sense of touch, auditory, and long-term memory when constructing mental models of the world. It is apparent that all these remaining modalities contribute to cognitive efforts. However, it was also discussed earlier that of these modalities, the sense of touch is primarily engaged in the cognitive efforts of people with visual impairment. A relatively large amount of space in the somatosensory cortex is assigned to the hands, which implies that information related to the sense of touch plays a crucial role in interacting with the world. Additionally, brain plasticity theory suggests that people who are visually impaired typically have enhanced capabilities in the remaining modalities. In particular, sensitivity relevant to the touch sensory modality is significantly enhanced. The sense of touch is considered an important and effective way for people with visual impairment to interact with the world. Minogue and Jones (2006) introduced the notion that human capability to deal with information related to the sense of haptic is superior to the capability to deal with visual and auditory information. The following section is devoted to a discussion of the potential for the use of touch in a modification of PICTIVE's prototyping technique to accommodate participants with visual impairment in haptic user interface design activities. To obtain an in-depth understanding of haptic user interface design activities, three components (i.e., computer, human, and interaction) are first reviewed.

Computer: First, the target system, haptic technology is primarily engaged in a virtual environment where haptic widgets are presented. In graphical user interface designs, the term “interface” refers to visible, software elements of a system, for instance windows, icons, menus, and pointers (also called WIMP) (Carneiro et al., 2004). Traditionally, a system’s overall screen organization and layout are considered a critical components of user interface designs, leading to significant impacts on usability (Parush, Shwarts, Shtub, & Chandra, 2005). In particular, the selection of color is an important aspect of graphical user interface design (Becker, Tu, & Kim, 2006). Intended users’ visual acuity, contrast sensitivity, visual field, and age-related vision degradation are often reflected in user interface designs. Almost all graphical user interface designs are facilitated by including information from a user’s retina. On the other hand, haptic user interfaces are primarily focused on the types of touch. More specifically, haptic user interfaces can be facilitated by both kinesthetic and cutaneous touch interfaces. Haptic user interfaces should be developed by comprehensively considering intended users’ biomechanical, sensorimotor, and cognitive capabilities (Kortum, 2008). For instance, mechanical features of haptic user interfaces (e.g., workspace size, force magnitude, force bandwidth, velocity, acceleration, mass, sensing, acuteness, and accuracy) should be well matched to the characteristics of intended users. The mechanical features should also ensure safety for users in its operation (Kortum, 2008). In addition to such mechanical aspects of haptic user interfaces, cognitive aspects should also be carefully taken into account. There has been a general lack of consideration about the development of information or contents presented in virtual environments (e.g., user interface designs to enhance user’s experiences with discrimination of haptic widgets or navigation in a virtual environment) (Kim, Nam, & Smith-Jackson, 2008).

Human: Intended users in this research are individuals who have visual impairment. They interact with the world by the sense of touch, which enables them to obtain relevant information about an object. Lederman and Klatzky (1987) modeled hand movement patterns linked to one’s desired knowledge about an object, which is referred to as haptic exploratory procedures. For example, people push their hands against an object’s surface or twist the object when they want to assess the rigidity of the object. In this regard, a specific movement of the hands refers to ‘pressure’, and the desired knowledge is the object's 'rigidity.' People with visual impairment can take advantage of haptic exploratory procedures to communicate with environments (Carneiro et al., 2004). Many physical features of an object, such as texture, material, and curvature, can be understood by touch. Touch can serve as "windows" in identifying an object in the same way as the eyes do; touch contributes to contacting the same part of an object multiple times in any order (Hatwell et al., 2003). More specifically, the mechanism of obtaining information by touch consists of two phases: (1) a generalized procedure, and (2) specific exploratory procedures (Abascal, 2002). The first phase is to use the generalized procedure in which human beings use their hands and collect vague haptic and tactile information about an object. In the second phase, a particular object's features (e.g., texture, curvature) are obtained through exploratory procedures (e.g., lateral motion, pressure, static contact, unsupported holding, enclosure, and contour following). Table 9 displays haptic exploratory procedures linked to objects' features (Kahol & Panchanathan, 2008; Lederman et al., 1987).

Table 9. Specific object features detected by exploratory procedures (adopted from Lederman, 1987)
[Used with permission from Elsevier]

Feature	Exploratory Procedure	Movement
Texture	Lateral motion	
Hardness	Pressure	
Temperature	Static contact	
Weight	Unsupported holding	
Global shape, volume	Enclosure	

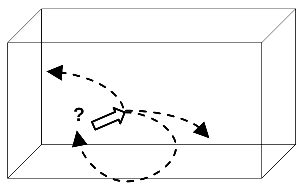
Global shape, exact shape	Contour following	

Lederman and Klatzky's model of hand movements (i.e., haptic exploratory procedures) supports the notion that people with visual impairment are able to perceive *material properties* by using the sense of touch. By considering their model, various material properties (e.g., texture, hardness, and shape) can be assigned to prototyping artifacts so that in prototyping activities users with visual impairment can distinguish them by touch. Furthermore, specific meanings can be assigned to each material property of a given prototyping artifact because the original PICTIVE technique assigns specific meanings to each color in the prototyping artifact (e.g., office supplies). Such material properties, for instance, can also be used as user interface components (e.g., drop-down boxes, menu bars, and other icons) because participants in the original PICTIVE technique attempt to design graphical user interfaces by using colored office supplies. The model can be applied to a prototyping artifact that is fixed at one location without any consideration of its movements and its relations with other prototyping artifacts.

Hatwell et al. claimed that the sense of touch could also contribute to the perception of *spatial properties*, which play a critical role in perceiving and discriminating locations of stimuli in environments. Spatial properties include: localization, length, line, and orientation (Hatwell et al., 2003). In general, people attempt to trace a certain standard to three locations, in the vertical (median sagittal plane), horizontal (midtransverse plane), and oblique (mid-transverse plane) directions (Millar, 1994). For instance, a reference frame is often used to localize a stimulus in the environment. Thus, spatial information such as location, distance, and direction is identified with respect to oneself or to an external point or coordinate, which is called spatial coding (Millar, 1994). In particular, people who cannot see are able to receive benefits from a self-referent frame (also referred to as a body-centered frame). For example, the location of an object can be identified by coding one's hand position when touching an object with reference to the midline of the body. Another type of spatial coding is the external frame. Instead of *one's body*, an individual can locate an object by using cues from the *external* environment for reference. Millar (1994) contended that the convergence of body-centered kinaesthetic and proprioceptive information is a reliable way of spatial coding in haptic conditions. The primary contribution of kinaethetic information coming from a body or a body part is to serve as a location anchor for starting or stopping a movement. A body or a body part can also be used as a coordinate reference frame to identify the location of an object. However, if an object's initial position is changed or an observer is replaced, movement sequences are coded (Millar, 1994). To facilitate movement coding, additional cues or frames should be provided as a reference. Taken together, this research suggests that users who are visually impaired should be provided with a cardboard box (i.e., a 3-dimensional cube with x, y, and z-axes) for their additional frame. Within the inside space of the box, they can easily identify their positions and the positions of the prototyping artifacts.

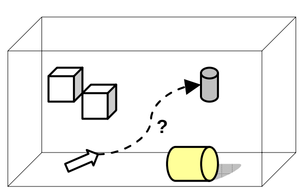
Interaction: Interaction in the HCI domain generally refers to the communication between a computer and a user. The communication between haptic technology and users with visual impairment is facilitated by exploring a virtual environment of haptic technology or experiencing haptic widgets in a virtual environment. MacLean (2000) presented a model of multi-sensory interaction associated with haptic technology. The model is composed of a user, an interaction model, a physical interface, and an environment. The interaction model specifically defines the relationship between multimodal sensory inputs and environments. The multimodal sensory inputs are treated as the combined information from multiple sensory modalities, such as touch and sound. However, how the sense of touch contributes to interactions is not illustrated clearly enough. Fortunately, Sjostrom (2001b) introduced four types of fundamental interactions between haptic technology and a user. The interactions include: (1) navigation in the virtual environment, (2) finding objects and overview, (3) understanding features of an object, and (4) discrimination of objects. To facilitate navigation in the virtual environment, it is recommended that, for example, a corner of a workspace be assigned as a reference point. Because the workspace is based on a 3-D virtual environment, there is a high likelihood that users become lost. There are questions with regard to users who are visually impaired: "How should it be designed to facilitate navigation in the virtual environment?", "How should it be designed to effectively deal with disabled buttons or navigation menus that are not supposed to allow double clicks?" Because such a disabled button can still be used as a reference point for users with visual impairment, it is critical to design it properly. Solutions might include making the disabled buttons remain touchable, but assign different types of textures to the disabled buttons (see Table 10).

Table 10. Navigation

Haptic interaction	Situation	Design aspects
Navigation	Users are exploring the virtual environments (VE). There is a possibility that users become lost. They might have difficulty identifying where they are located in VE. 	How should it be designed to facilitate navigation in VE? (e.g., the corner of a room as reference point) How should it be designed to effectively deal with disabled buttons that are unclickable? Generally, such a button in VE can be used as a reference point even though it becomes nonfunctional. (e.g., the disabled buttons remain touchable and different types of texture are assigned to the disabled buttons.)

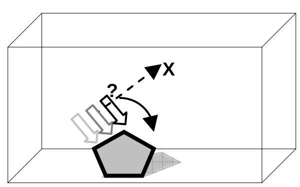
In addition to exploring the virtual space, finding a desired object and getting an overview are also fundamental activities. Regardless of the purposes of haptic technology (e.g., a game, education), it is common that multiple and various haptic widgets are presented in the 3-D space. Even if two haptic widgets were placed close to each other, it would be easy for a user to miss the target object. This main concern leads to the question, “How should it be designed to help users easily find objects?” Sjostrom (2001b) recommended some design ideas, such as shortening distances between objects, using different material properties (e.g., texture, hardness, shape), using magnetic or enlarged interaction forces between objects, or using grooves or path-ride (see Table 11).

Table 11. Finding objects and an overview

Haptic interaction	Situation	Design aspects
Finding objects and an overview	Users should find a specific haptic widget. The specific haptic widget exists along with several other widgets. Additionally, users must be able to get an overview. 	How should it be designed to help users easily find objects? (e.g., possible clues include ‘changing distances between objects.’ ‘different textures or sizes,’ ‘enlarged interaction - magnetic objects’, ‘path-ride,’ ‘grooves,’ etc.) How should it be designed to provide an overview?

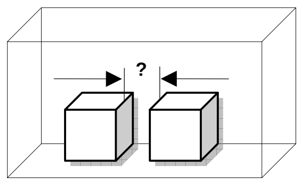
Understanding features of an object is greatly facilitated by a user's hand and finger movements. In contrast with the sense of vision, the sense of touch is less likely to contribute successfully to a prediction. For example, if a user who explored the virtual environment and finally found the desired haptic widget among the others, the next activity for the user might be to recognize the object's features, such as shape. Consequently, the user might intend to keep moving their hands and fingers on the surface of the target object to feel and understand its global shape. However, a haptic widget can be presented as a three-dimensional solid object bounded by four (tetrahedron), six (cube), eight (octahedron), 12 (dodecahedron), or 20 (icosahedron) sides. These multiple sides result in angles and sharp edges. It is likely that a user will lose contact when touching the surface of the target object (see Table 12). One concern is: "How should it be designed to keep users from losing contact with the widget, especially when moving past a sharp corner?"

Table 12. Understanding an object

Haptic interaction	Situation	Design aspects
Understanding an object	Users approach the widget to locate it. After users find the position of the widget, they keep moving their hands/fingers over the surface of the widget to feel and understand it. However, the haptic widget contains very sharp edges. Users probably lose contact. 	How should it be designed to keep users from losing contact with the widget, especially when moving past a sharp corner? (e.g., use a minimal degree of sharpness)

Sometimes, an interaction occurs between a pair of objects. Some users might move their fingers and hands while touching and feeling an object's surface. There is a risk that users will fail to recognize the gap between two objects located closely together. These two objects will probably be considered a single object. One concern is how it should be designed to help users distinguish two widgets located closely together (see Table 13).

Table 13. Discrimination of objects

Haptic interaction	Situation	Design aspects
Haptic widgets	Users are feeling across a thin gap between two widgets, but users' fingers move quickly. There is a risk that users will fail to recognize the gap. Consequently, the two widgets are probably recognized as just a single widget. 	How should it be designed to help users distinguish two widgets (e.g., two buttons on a menu interface) that are closely located? (e.g., a magnetic wall located between two objects)

In summary, while constructing mental models of the world, the sense of touch primarily works best for people with visual impairment, as does the sense of vision for people without visual impairment. Furthermore, brain plasticity theory suggests that people who are visually impaired typically have enhanced capabilities in the haptic modality. The sense of touch is able to help those with visual impairment to contribute to haptic user interface designs. The present study has discussed how the use of touch has the potential for accommodating participants with visual impairment, especially in haptic user interface design. As shown in Figure 39, the target system, haptic technology, is represented by cutaneous and kinesthetic touch interfaces. Users with visual impairment communicate with the target system through the movements of their hands and fingers, which possess the capability of perceiving many features (e.g., material and spatial information) of haptic widgets. The basics haptic interactions (e.g., navigation, finding objects, an overview, understanding an object, and discrimination of objects) remain unclear, leading to the question of how they should be defined for users with visual impairment.

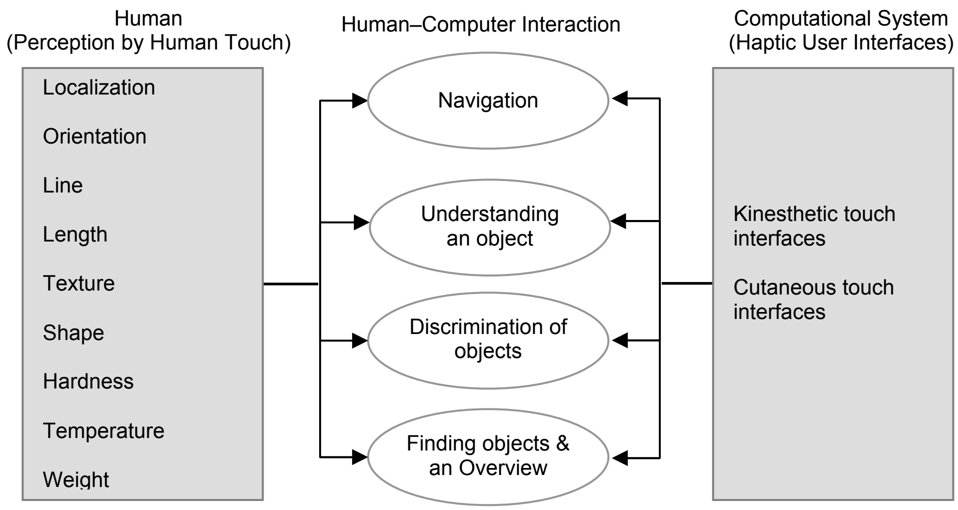


Figure 39. A schema of the interactions between haptic technology and a user with visual impairment

The vision-based, low-fidelity prototyping technique of PICTIVE can be modified, for example, by allowing users with visual impairment to communicate with prototypes through their sense of touch. It implies that people who are visually impaired design non-visual interfaces (e.g., haptic interfaces) by means of non-visual communication (e.g., the sense of touch). It could be named 'what you feel is what you get (WYFIWYG),' because content tangibly presented in design development will look very similar to the final outcome. Keyson and Parsons (1990) pointed out that a successful prototyping tool is one that enables a designer to easily modify designs and conduct an iterative design. A touch-based prototyping technique must enable participants with visual impairment to easily change interface designs by touch. It is anticipated that participants (i.e., users with visual impairment and sighted designers) are able to participate equally and effectively in haptic interface designs by a non-visual interaction prototyping technique, such as a touch-based prototyping technique.

Replacement of visually based prototyping techniques with touch-based prototyping techniques: A video camera and a collection of design objects that participants manipulate during design sessions are prepared. The video camera is used to record the design sessions and the voices of participants. It is unnecessary to hide the camera.

The design objects fall into two categories. The first category is everyday office materials such as a rubber band, thread, glue, sandpaper, magnets, paper clips, adhesive tape, and thick paper. The second category includes haptic widgets (e.g., small-sized boxes for interface components) that are prepared by the designer in advance. While the conventional visually based PICTIVE method uses different colors for the design objects, the touch-based PICTIVE will use different textures for the design objects. For example, different grits of sandpaper will be attached to the surfaces of small-sized boxes.

In addition, the 3-dimensional (3-D) design space is a modified cardboard box (see Figure 40). The design space is referred to as an additional cue (or frame) and a simulated virtual environment, which is originally represented by haptic technology. The “ceiling” of the design space allows users or the designer to attach and hang a haptic widget from it, which is expected to improve participants’ sense of the 3-D environment. The sides of the design space are open to permit participants access to manipulate the design objects. The design equipment is described in Table 14.

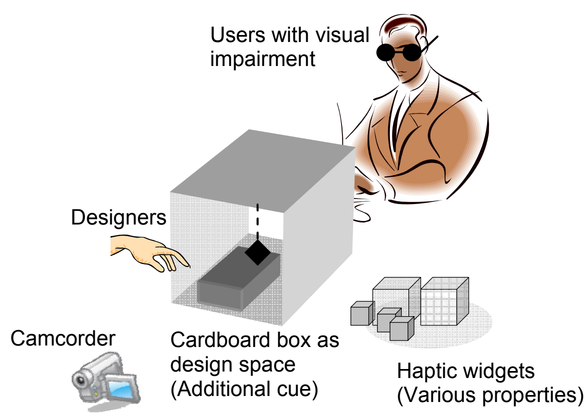


Figure 40. Conducting a touch-based prototyping technique in PICTIVE

Table 14. Equipment for touch-based prototyping in PICTIVE compared to vision-based prototyping

Vision-based, low-fidelity prototyping technique of PICTIVE	Touch-based, low-fidelity prototyping technique of PICTIVE
1. Video camera	1. Video camera
2. A collection of design objects	2. A collection of design objects
(1) every-day office materials: colored pens, colored highlighters, colored paper, colored Post-It notes of various sizes, colored stickers, colored labels, and colored paper clips	(1) every-day office materials: a rubber band, thread, glue, sandpaper, magnet, paper clip, adhesive tape, and thick paper (cardboard boxes)
(2) materials prepared by the developer to present multiple design exercises (e.g., command line, query fields, menu bars, and dialogue boxes) ▪ Icons: colored plastic icons for graphical user interfaces ▪ Pop-Up Events: a suite of paper images of pop-up events ▪ Menu Bars and Window Frames ▪ Several other tools to modify these items: brightly colored scissors, erasers, and the colored pens and highlighters	(2) materials prepared by the developer to present multiple design exercises ▪ haptic widgets (small-sized cardboard boxes for interface components, e.g., buttons) ▪ Several other tools to modify these items: scissors, glue, and adhesive tape
3. A design space in which prototyping activities are performed with design objects	3. A design space in which prototyping activities are performed with design objects ▪ 3-Dimensional design space that is made of thick paper (a cardboard box): The design space is referred to as an additional cue (or frame) and a simulated virtual environment, which is originally represented by haptic technology. The "ceiling" of the box allows users and the designer to attach and hang a haptic widget, which is expected to improve participants' sense of the 3-D environment. The sides of the box are open to permit participants access to manipulate the design objects.

2.11. Summary of the literature review

In addition to various traditional assistive technology applications, haptic technology is currently used to assist individuals with visual impairments in obtaining graphical information. Unfortunately, numerous users are dissatisfied with assistive technology applications, including haptic technology. The most significant reason for this is the failure to meet users' needs. Well-known regulations (e.g., Section 508) and design approaches (e.g., universal and inclusive designs) are aimed at reflecting the needs of users who have impairments. However, no particular consideration has been placed on individual differences *among* users who share the same category of disability (e.g., visual impairments, hearing impairments, or speaking impairments). Despite empirical evidence that there are individual differences among those classified as having the same disability, designers rely on presumptive design approaches and apply the same user interface designs for users in the same category of disability. Furthermore, although the majority of the population with visual impairment is comprised of individuals who retain some residual vision over total blindness, most previous studies have focused only on total blindness. In addition to vision, another factor that today's designers pay little attention to is aging. Residual vision (or low vision) is common in the elderly population.

People with visual impairment interact with the world though their own mental models that are constructed from different sources (e.g., long-term memory, auditory, and haptic), which can be factors, in turn, that influence their behaviors in response to the world. According to brain plasticity theory, brain cortical reorganizations occur in individuals who have impaired sensory modality, such as visual impairment, to compensate for their handicaps, which ultimately lead to enhanced capabilities in the remaining modalities. Vision is also one of the crucial routes that facilitate mental model construction. In contrast with those with total blindness, those with residual vision can take advantage of the visual modality. Additionally, people with residual vision can still expect brain plasticity induced by their deficient vision. This research, therefore, suggests that the use of both residual vision and the sense of touch will influence brain plasticity, which affects one's performance. The distinct performance of people with residual vision can be tied to their capability in the haptic modality.

Besides capability in the haptic modality, the interaction with haptic user interfaces is also influenced by brain plasticity. As discussed earlier, the brain of people who retain partial sight attempt to compensate for their visual sensory loss by altering their brain structure. Brain change would lead to the enhancement of one's haptic capability. Consequently, enhanced touch capability will alter the user's behavior in interacting with haptic user interfaces. The changes would be different for individuals who are totally blind or those with intact vision.

In existing design contexts, users with disabilities are less likely to be deeply involved in design development. In this regard, the participatory design approach can contribute to user involvement throughout the design development process. A variety of approaches to participatory design has been formed such as the ethnographic field method, cooperative design, contextual design, and PICTIVE.

Although the four approaches are under the same umbrella of participatory design, they are slightly different. Overall, PICTIVE has many benefits over the other design approaches.

PICTIVE can contribute to haptic user interface design. Because simple office supplies are used in PICTIVE, it is easier for users to understand the prototypes and features of the future target system. Consequently, users' active participation is expected in decision-making processes for interface designs. In addition, the users no longer rely on the designer, but they remain independent with regard to design problems. However, there is some doubt as to whether PICTIVE is valid for users who have visual impairments. PICTIVE was originally designed to help sighted people demonstrate what they want to see in a future system. Participants who are visually impaired cannot take advantage of such a prototyping technique. It is necessary to modify conventional prototyping techniques to allow participants who are visually impaired access to relevant information in design developments.

In interacting with the world, the sense of touch primarily works best for people with visual impairment, as does the sense of sight for people without visual impairment. In contrast with sighted people, those with visual impairment depend on other channels, such as the sense of touch, auditory, and long-term memory when constructing mental models of the world. It is apparent that all these remaining modalities contribute to cognitive efforts. However, of these modalities, the sense of touch is primarily engaged in the cognitive efforts of people with visual impairment. A relatively large amount of space in the somatosensory cortex is assigned to the hands, which implies that information related to the sense of touch plays a crucial role in interacting with the world. Furthermore, brain plasticity theory suggests that people who are visually impaired typically have enhanced capabilities in the remaining modalities. For instance, sensitivity in the auditory and touch sensory modalities is enhanced. However, the sense of touch is considered an ideal way to interact with the world. Lederman and Klatzky's haptic exploratory procedures modeled the pattern of hand movements that show the strategies of people with visual impairment exploring *material properties*. Hatwell et al. also claimed that the sense of touch plays a critical role in the perception of *spatial properties* in the real world. Minogue and Jones introduced the notion that human beings' capabilities to deal with information related to the sense of haptic is superior to their capabilities to deal with visual and auditory information. The use of the sense of touch should be encouraged in the design activity of PICTIVE. Ideally, a successful prototyping tool enables one to easily modify interface designs and conduct an iterative design. A touch-based prototyping technique can support participants with visual impairment so that interface designs can be easily modified by touch. The fundamental procedures of PICTIVE can be used, but the visually based prototyping technique of PICTIVE must be replaced with a touch-based technique.

To summarize, this research had two primary aims. The first was to investigate individual differences in users' capabilities in the haptic modality and user needs in HUIs. Particularly, age-related and vision-related individual differences were explored. The second was to develop a more accessible HUI design approach applicable to users with visual disabilities.

CHAPTER 3. STUDY 1: TARGET USERS

This research primarily focused on examining heterogeneous attributes of users' capabilities in the haptic modality and user needs in haptic user interfaces. More specifically, this research was accomplished by conducting three studies (see Figure 41). Study 1 explored individual differences in the haptic perception of individuals grouped by age and vision. Study 2 compared a modified PICTIVE with the original PICTIVE. Study 3 investigated the individual differences in haptic user interfaces in individuals grouped by age and vision. Detailed methodological approaches are summarized in Table 15.

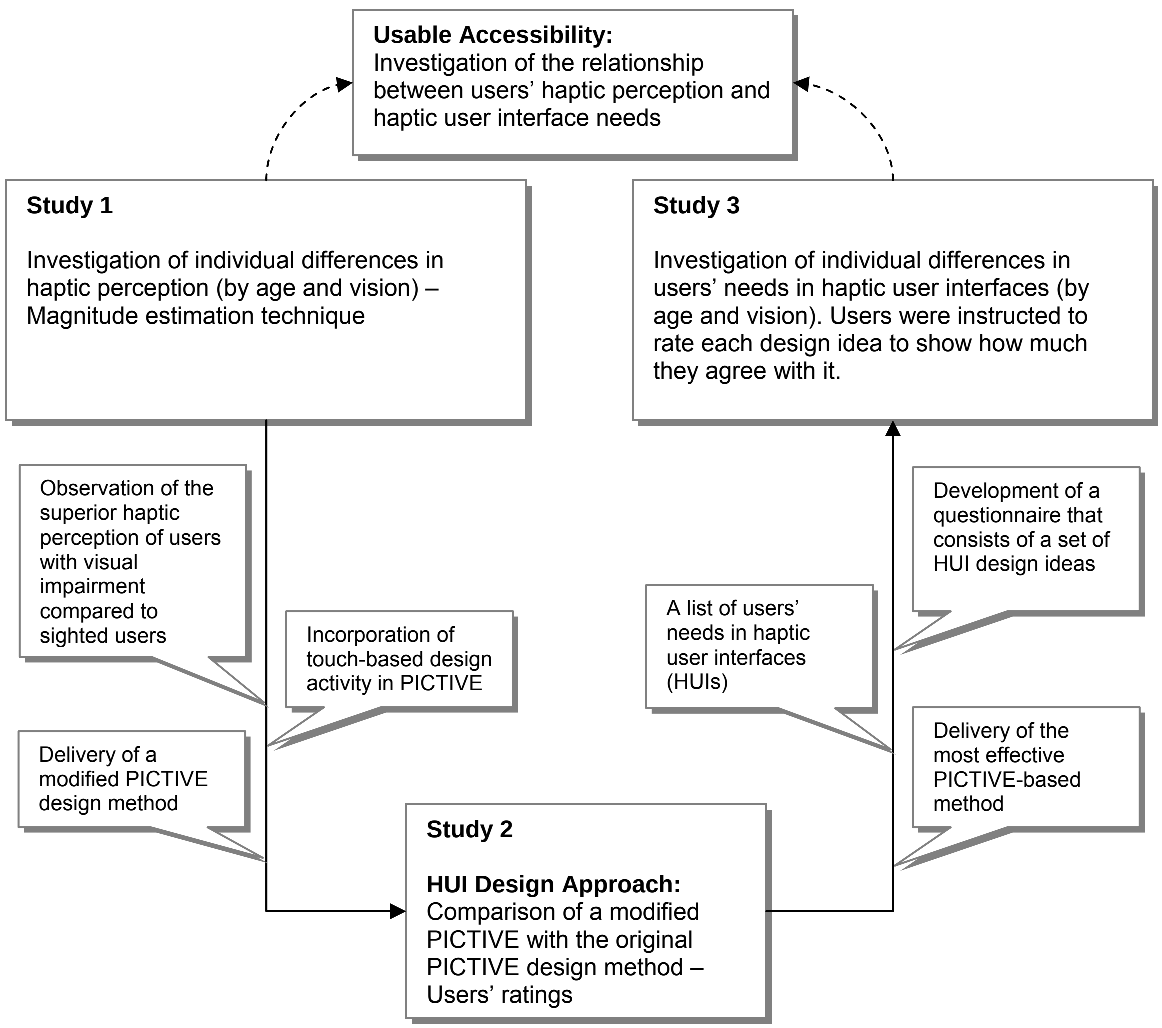


Figure 41. Model of the approaches

Table 15. Summary of the approaches

Study	Experimental design	Participants	Materials/ Equipment	Instruments	Data	Data analysis
1	▪ Mixed-factor design ▪ Investigation of individual differences in haptic perception associated with different ages and visual conditions	Age-related individual difference study ▪ 10 younger participants (younger than 30 years) with low vision ▪ 10 older participants (65 years or over) with low vision Vision-related individual difference study ▪ 10 participants with low vision (younger than 30 years) ▪ 10 participants with intact vision (younger than 30 years)	Different grades of sandpaper; fine (120 grit), very fine (320 grit), extra fine (400 grit)	Rating scale (magnitude estimation technique)	Numerical values assigned to the estimated magnitude of a sensory attribute (e.g., perceived roughness)	Mann-Whitney test Friedman's analysis of variance (ANOVA) Adjusted Rank Transform test
2	▪ Between-subject design ▪ Investigation of the effectiveness of a modified PICTIVE by comparing with the original PICTIVE	▪ 10 participants (5 younger and 5 older) in the modified PICTIVE ▪ 10 participants (5 younger and 5 older) in the original PICTIVE	Video camera, a collection of design objects (office materials and haptic widgets)	Questionnaire (a combination of closed and open-ended questions) to investigate users' satisfaction	Frequency of gestures, frequency of statements, satisfaction, and time spent on design activities	Independent-samples *t*-test and content analysis
3	▪ Between-subject design ▪ Investigation of individual differences in haptic user interfaces associated with different ages and visual conditions	Age-related individual difference study ▪ 10 younger participants (younger than 30 years) with low vision ▪ 10 older participants (65 years or over) with low vision Vision-related individual difference study ▪ 10 participants with low vision (younger than 30 years) ▪ 10 participants with intact vision (younger than 30 years)	A list of haptic user interface preferences generated in Study 2	Questionnaire (closed-ended questions)	Each participant's agreement (numerical value)	Independent-samples *t*-test Mann-Whitney test

3.1. Method

Study 1 aimed to understand the target users in terms of haptic perception. The target users were classified by age (younger and older) and vision (low vision and intact vision). The target users' haptic perception was measured by a magnitude estimation technique. Magnitude estimation is a psychophysical scaling technique that helps determine how much of a given objective stimuli an individual subjectively perceives (Stevens, 1971). Analysis of haptic perception is often conducted by a physical measurement of roughness (Bergmann Tiest & Kappers, 2006a), which is typically measured by using sandpaper stimuli (Bergmann Tiest et al., 2007; Diamond et al., 2001; Lederman & Abbott, 1981; Suzuki et al., 2008; Verrillo et al., 1999). Therefore, the haptic perception of participants in this research was investigated in a roughness test using sandpaper samples.

3.1.1. Experimental design

Study 1 was divided into two stages: an age-related individual-difference study and a vision-related individual-difference study (see Table 16). One key task was to examine whether individuals with the same vision status (i.e., low vision) were differentially influenced by their age when perceiving stimuli. Another concern was whether individuals in the same age range were influenced by their vision condition differently when perceiving stimuli. However, the interaction of (age)*(vision)*(stimuli) was not considered in this research. How an older adult in category 0 (i.e., no visual impairments) responds to sandpaper with different grits did not have a bearing on this research. According to the literature reviews, most elderly individuals are affected by age and have visual impairments in categories 1, 2, 3, or 4, but not category 0 (no visual impairments). Thus, the two studies were conducted separately. Independent and dependent variables are listed in Table 16.

Table 16. Independent and dependent variables

	Age-related individual-difference study	Vision-related individual-difference study
Independent variables	▪ Age (younger and older) ▪ Objective stimuli (fine, very fine, and extra fine sandpaper)	▪ Vision (low vision and intact vision) ▪ Objective stimuli (fine, very fine, and extra fine sandpaper)
Dependent variable	Perceived intensity of objective stimuli (i.e., perceived roughness)	Perceived intensity of objective stimuli (i.e., perceived roughness)

Structural model for the aging study

The age-related individual difference study had a mixed-factor design, consisting of factor A (two age groups) and factor B (three different grits of sandpaper).

Observation = Population Mean + Main Effect + Interaction + Random Error

$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{k(i)} + \alpha\beta_{ij} + \beta\gamma_{jk(i)} + \varepsilon_{l(ijk)}$

α_i = fixed effect of the age groups (factor A)

β_j = fixed effect of the stimulus groups (factor B)

$\gamma_{k(i)}$ = effect of the participant (random) in each group

$\alpha\beta_{ij}$ = interaction effects of the age groups and stimulus groups

$\beta\gamma_{jk(i)}$ = effect of a particular level of repeated measures of factor B on the particular individual nested within the group

$\varepsilon_{l(ijk)}$ = random effect of the k^{th} participant receiving the i^{th} age group followed by the j^{th} stimulus

Structural model for the vision-related individual difference study

The vision-related individual difference study had a mixed-factor design, consisting of factor A (two vision groups) and factor B (three different grits of sandpaper).

Observation = Population Mean + Main Effect + Interaction + Random Error

$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{k(i)} + \alpha\beta_{ij} + \beta\gamma_{jk(i)} + \varepsilon_{l(ijk)}$

α_i = fixed effect of the vision groups (factor A)

β_j = fixed effect of the stimulus groups (factor B)

$\gamma_{k(i)}$ = effect of the participant (random) in each group

$\alpha\beta_{ij}$ = interaction effects of the age groups and stimulus groups

$\beta\gamma_{jk(i)}$ = effect of a particular level of repeated measures of factor B on the particular individual nested within the group

$\varepsilon_{l(ijk)}$ = random effect of the kth participant receiving the ith age group followed by the jth stimulus group

3.1.2. Participants

For this research, sample size was statistically estimated using the formula below (Ott & Longnecker, 2001; Quinn & Keough, 2002).

$$n \geq \frac{\sigma^2 \left(z_{\alpha/2}\right)^2}{\Delta^2}$$

,where σ is the standard deviation of performance time judging relative magnitude with computer-generated haptic properties, and Δ is the difference between μ_0 and μ_1. In general, these values (i.e., σ and Δ) are determined based on the results of previously published studies with similar subject matter and participants (Quinn et al., 2002). The present research used a previous study by Douglas and Willson (2007) as its referent. In the study of Douglas and Willson, sighted participants and those with visual impairment were assessed in terms of the effect of their haptic perception on task performance. The standard deviation was 5.02 (Douglas & Willson, 2007). Additionally, the difference between μ_0 and μ_1 (i.e., the minimum difference) was considered to be 4 (Douglas & Willson, 2007). Given α = .05, 10 participants in each group should be sufficient to reliably detect a statistical difference in the haptic-related performance, with a risk for a Type I error of .05 and a Type II error of < .30, with a power greater than .70. This sample size (*n* = 10 / group) also meets the recommendation of ISO 11056:1999 (E) that a magnitude estimation experiment be conducted with a minimum of five assessors (ASTM, 1999).

Older participants in this research were defined as those over the age of 65. In fact, there is no universal agreement at what age one should be categorized as old (World Health Organization, 2008b). For instance, people over 65 years of age are generally referred to as elderly individuals in most countries; on the other hand, 50 or 55 years of age is old in some countries in Africa (World Health Organization, 2008b). In addition, diverse definitions of “elderly” are also seen in institutions. For instance, the United Nations (UN) defines individuals over 60 years of age as the older population (World Health Organization, 2008b). The Centers for Disease Control and Prevention (CDC) views adults aged 65 years or older as elderly (Centers for Disease Control and Prevention, 2007).

The use of cognitive function was considered as one possible means to distinguish between "younger" and "older" individuals. In recent years, various psychologists have specialized in the field of cognitive aging—that is, the study of what cognitive changes occur as people grow older. Tim Salthouse has produced the most extensive and carefully argued work with regard to ageing and cognition (Baddeley, 2007). Salthouse's theory (Salthouse, 1992; Salthouse, 1996) indicates that the variance in cognitive function resulting from age can be understood in terms of the speed of information processing (e.g., encoding and retrieval). The speed of information processing and working memory capacity decline with age, thereby limiting the rate at which older adults can learn new technology (Liu & Park, 2003; Schieber, 2003). Indeed, several studies have found empirical evidence that would support Salthouse's processing speed theory, and a decline in performance on timed tests (reflective of declining speed of information processing) was observed particularly in participants age 65 and over (Cooper et al., 1997; Llaneras, Swezey, & Brock, 1997; Perlmutter, 1994; Ranney & Simmons, 1997). Furthermore, vision loss is most common in adults age 65 and over (Lin & Williges, 1997). Thus, in this research, those 65 years of age and older were considered older participants. Older participants were recruited from a retirement community (i.e., Warm Hearth Village) in Blacksburg, VA, at the Roanoke Alliance for the Visually Enabled (RAVE), Roanoke, VA, and other local communities in Montgomery County, VA.

On the other hand, younger participants were defined as those under the age of 30 in this research. Cognitive decline associated with information processing and working memory capacity begins around age 30 (Mahncke, Bronstone, & Merzenich, 2006; Salthouse, 1982). In addition, Gorman and Fisher (1997) have identified cognitive aging in participants age 60 or older, but never in participants younger than 30. Thus, attempts were made to focus on recruiting individuals younger than 30 years old.

In this research, the classifications for visual impairment described by WHO (2008c) were used. Thus, an individual with residual vision (or low vision) refers to one who is visually impaired but partially sighted, which is further divided into two categories: category 1 (moderate visual impairment) or category 2 (severe visual impairment). The vision acuity of individuals in category 1 was worse than 20/70, but equal to or better than 20/200. The vision acuity of individuals in category 2 was worse than 20/200, but equal to or better than 20/400. An individual with intact vision was defined as belonging to category 0 (no visual impairment), where vision acuity was equal to or better than 20/70.

In total, the age-related individual-difference study included 10 younger individuals (less than 30 years of age) with low vision and 10 older individuals (65 years of age or over) with low vision. On the other hand, the vision-related individual-difference study involved 10 individuals with low vision (less than 30 years of age) and 10 individuals with intact vision (less than 30 years of age). Table 17 shows the classification and characteristics of participants.

Table 17. Participant classifications

	Age-related individual-difference study			Vision-related individual-difference study		
Participants	▪ Age (younger or older) o 10 younger participants (less than 30 years of age) with low vision o 10 older participants (65 years of age or over) with low vision			▪ Vision (low vision or intact vision) o 10 participants with low vision (less than 30 years of age) o 10 participants with intact vision (less than 30 years of age)		
		Younger	Older		Low vision	Intact vision
	Mean age (SD)	20.70 (5.21)	81.90 (6.87)	Mean age (SD)	20.70 (5.21)	21.70 (3.13)
	Mean age of onset of visual impairments (SD)	5.30 (8.98)	60.30 (17.42)	Mean age of onset of visual impairments (SD)	5.30 (8.98)	N/A
	Mean duration of visual impairments (SD)	15.40 (8.18)	21.60 (16.37)	Mean duration of visual impairments (SD)	15.40 (8.18)	N/A
	Mean visual acuity in decimal notation (SD)	0.13 (0.11)	0.18 (0.11)	Mean visual acuity in decimal notation (SD)	0.13 (0.11)	0.66 (0.30)

3.1.3. Materials and equipment

The objective stimuli were generated by rectangular samples (9 in x 11 in) of standard commercial grades of sandpaper (e.g., 3M™ aluminum oxide sandpaper). This research referred to the ISO 6344 standard (International Organization for Standardization, 1998) that defines different grades of sandpaper: fine (120 grit), very fine (320 grit), and extra fine (400 grit). The grit was a reference to the number of abrasive particles per inch of sandpaper. Each participant received the same objective stimuli. In other words, any used sandpaper was immediately discarded so that each participant was given new sandpaper samples. In addition, alcohol was used to clean the surface of participants' fingers thoroughly before each test.

Each participant's vision acuity was measured by use of a Snellen chart, which is the most widely used tool in visual acuity assessment. The initial prototype of this chart was introduced in 1862 by Dutch ophthalmologist Hermann Snellen. Afterwards, the original chart was modified by other scholars before become standardized in its current form (Falkenstein et al., 2007). A participant was instructed to stand behind a line 20 feet from a wall-mounted Snellen vision chart. The participant covered one eye with an eye spoon and read aloud from the top line of letters (i.e., the largest letter) to the smallest line of letters that a participant can see. If a participant used the eye spoon, he or she was instructed not to apply pressure to the occluded eye because pressure can cause blurred vision and thus skew the results (Haupt, 2008). This procedure was repeated for the other eye. The vision of each eye was recorded separately. The participant's vision acuity was represented by the acuity in the better eye with the best possible correction, according to the WHO classification of visual impairment.

3.1.4. Procedure

Study procedures consisted of five steps: IRB, familiarity, vision acuity check, magnitude estimation experiment, and post-experiment (see Figure 42).

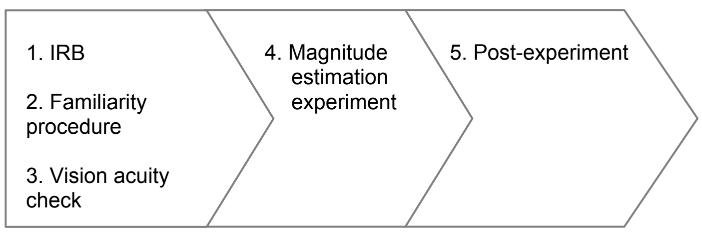


Figure 42. Procedures for magnitude estimation experiments

A representative participant with visual impairment was asked to check the accessibility of the location for the experiment. For example, a person with visual impairment conducted a walkthrough to make sure that the location for the experiment was safe from any potential barriers. It was also ensured that all documents in the design sessions were accessible to a participant through various modes, for example, Braille, audio tape, designer's oral explanations, or descriptions on a computer screen (in this case, screen-reader software was provided).

The participant was asked to review the Virginia Polytechnic Institute and State University (or Virginia Tech) IRB informed consent form and sign it. The IRB informed consent form was in several formats, including Braille and large font paper. A participant was given the informed consent form in their preferred format. A researcher indicated the location for signature, if needed. A participant kept one copy of the consent form, but the other copy was kept by the researcher.

The participant was guided to become familiar with the experimental equipment, the procedures, and the location where the experiments were conducted, including the arrangement of chairs, desks, doors, and safety-related gadgets, if available. After the orientation procedure, the researcher did not move anything without informing the participant. In addition, there were other considerations the researcher kept in mind: (a) explaining unusual noises and activities (e.g., clicking camcorder buttons, opening/shutting doors), (b) offering an elbow to lead the participant, (c) giving directions about where to be seated, (d) not interacting with a guide dog or service animal, and (e) telling a participant where there was a room for the guide dog. A short amount of time was assigned to a warm-up period in which a participant and the designer discussed any personal topics.

A Snellen vision chart was used to measure a participant's vision acuity in order to ensure that he or she fell into one of two categories: category 1 (moderate visual impairment) or category 2 (severe visual impairment).

The magnitude estimation test was conducted as described in international standard protocols (American Society for Testing and Materials, 1996; International Organization for Standardization, 1999). A participant was given a series of stimuli (e.g., sandpaper samples) and instructed to touch them with the fingers of the dominant hand. Because the speed of one's finger movements is less likely to influence one's perceived roughness, at least within the range of approximately 1-25 cm/s (Suzuki et al., 2008), there was no requirement for a participant to finish a magnitude estimation in a certain amount of time. A participant had sufficient time to explore a given stimulus. In addition, a participant was allowed to move the fingers around and touch a sandpaper sample from all directions. A researcher helped a participant locate a sandpaper sample if needed. A participant was also permitted to touch an assigned sandpaper sample as often he or she wanted. A participant who had low vision was allowed to use his or her vision. To avoid a decline in the sensitivity of a participant's fingers, a short time break was assigned to a participant when he or she felt the fingers became less sensitive or if he or she felt discomfort. However, the present study followed the recommendation of Suzuki et al. (2008) who set an upper limit for the number of trials: a participant should be required to take a break after every 28 judgments.

As Stevens (1971) recommended, one judgment was completed per stimulus per participant. A pre-identified reference sample (or "modulus") was used to develop a common scale among participants. The reference was a numeric value fixed by the researcher. A participant was instructed to assign numerical values to the magnitude of given stimuli (i.e., three different grits of sandpaper samples) compared to the fixed value. For example, a participant was told that, if the roughness of a piece of sandpaper seemed twice as intense as the previous sandpaper sample (e.g., the first value = 10), a number twice as large (e.g., 20) should be assigned. According to ISO 11056 (International Organization for Standardization, 1998), the scale should have no upper limit; however, the value 0 should be assigned only in exceptional cases, for example, when no attribute was perceived. A participant was asked to use round numbers such as 5, 10, and 15 in the scaling technique.

After the magnitude estimation experiments, a participant was compensated at a rate of $10 per hour. Sessions lasted approximately 30 to 45 minutes.

3.1.5. Data analysis

Magnitude estimation data are typically log-normally distributed (Chambers IV et al., 1996). Therefore, a data analysis was performed with the data log transformed. In general, the value 0 causes a problem in data analysis in magnitude estimation because there are no logs of 0. The American Society for Testing and Materials (or ASTM) suggested methods for managing zeros: (a) replace all zeros with an arbitrarily small number or (b) instructing participants not to use zeros (Chambers IV et al., 1996). Given a set of modified data, Shapiro-Wilk tests were performed to check the normality of the data. The results revealed that the set of modified data included non-normal data, making a parametric test (e.g., a two-way mixed analysis of variance) unsuitable for the age-related and the vision-related individual-difference studies. Thus, non-parametric data analyses specifically the Mann-Whitney test and Friedman's analysis of variance (ANOVA) were conducted. These tests contributed to the investigation of the major effects of age, vision, and objective stimulus (i.e., sandpaper). To explore the interactions of age x sandpaper and vision x sandpaper, an Adjusted Rank Transform (ART) test was conducted (Sawilowsky, 1990).

The age-related individual-difference study sought to answer the following research question: To what extent do younger and older users with residual vision share a common haptic perception of the same objective stimulus? A statistical analysis was performed on the dependent variable (i.e., perceived roughness) with $\alpha \leq .05$ to explore age and objective stimulus effects. In addition, interaction effects were investigated. In the age-related individual-difference study, the following alternative hypotheses were considered:

- [Age effect] Perceived roughness will be different for different age groups.
- [Objective stimulus effect] Perceived roughness will be different based on variations in objective stimuli.

The vision-related individual-difference study sought to answer the following research question: To what extent do users with different vision statuses share a common haptic perception of the same objective stimulus? A statistical analysis was performed on the dependent variable (i.e., perceived roughness) with $\alpha \leq .05$ to explore vision and objective stimulus effects. In addition, interaction effects were also investigated. In the vision-related individual difference study, the following alternative hypotheses were considered:

- [Vision effect] Perceived roughness will be different for different vision groups.
- [Objective stimulus effect] Perceived roughness will be different based on variations in objective stimuli.

3.2. Results

3.2.1. Age-related individual-difference study

Research Question: To what extent do younger and older users with low vision share a common perception of the same objective stimulus?

H_a: Perceived roughness will be different for different age groups.

H_a: Perceived roughness will be different based on variations in objective stimuli.

The AGE x SANDPAPER interaction was not statistically significant, $F(2, 36) = 1.06$, $p = .36$ (younger, 120 grit [$M = 5.76$, $SD = 0.20$], 320 grit [$M = 5.44$, $SD = 0.28$], 400 grit [$M = 5.00$, $SD = 0.43$]; older, 120 grit [$M = 5.69$, $SD = 0.20$], 320 grit [$M = 5.52$, $SD = 0.11$], 400 grit [$M = 4.82$, $SD = 0.41$]). The main effect of AGE was not statistically significant, $U = 414$, $p = .59$ (younger, $M = 5.40$, $SD = 0.44$; older, $M = 5.34$, *SD* = 0.47). However, the analysis did reveal a statistically significant effect of SANDPAPER, $\chi^2(2) = 38.03$, $p < .001$. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was also applied and so all effects were reported at a .02 level of significance. Wilcoxon tests found that the perceived roughness at 120 grit, 320 grit, and 400 grit sandpaper samples were statistically significantly different from each other ($p < .02$). The sample medians are displayed in Figure 43 (for 120 grit, *Mdn* = 5.70; for 320 grit, *Mdn* = 5.52; for 400 grit, *Mdn* = 4.95).

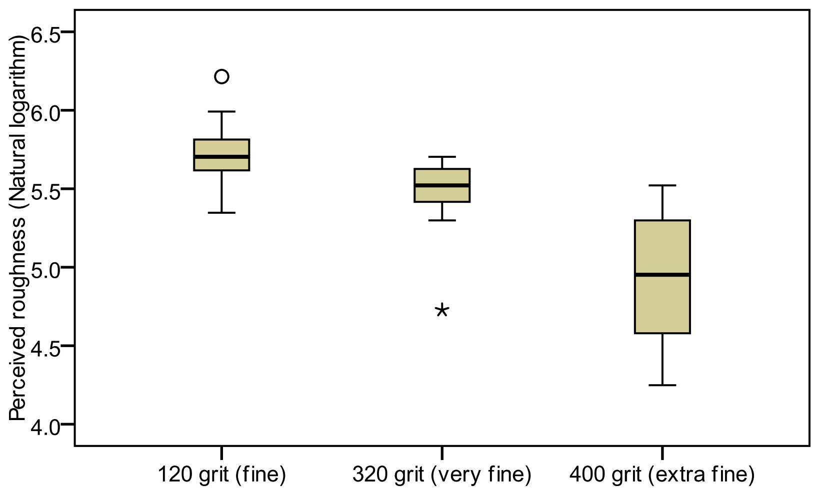


Figure 43. The perceived intensity of physical stimuli (Fine, Very Fine, and Extra Fine) (*p* < .02)

3.2.2. Vision-related individual difference study

Research Question: To what extent do users with different vision statuses (i.e., low vision and intact vision) share a common perception of the same objective stimulus?

H_a: Perceived roughness will be different for different vision groups.

H_a: Perceived roughness will be different based on based on variations in objective stimuli.

The VISION x SANDPAPER interaction was not statistically significant, $F(2, 36) = 0.26$, $p = 0.77$ (low vision group, 120 grit [*M* = 5.76, *SD* = 0.20], 320 grit [*M* = 5.44, *SD* = 0.28], 400 grit [*M* = 5.00, *SD* = 0.43]; sighted group, 120 grit [*M* = 5.76, *SD* = 0.27], 320 grit [*M* = 5.57, *SD* = 0.14], 400 grit [*M* = 5.19, *SD* = 0.16]). The main effect of VISION was not statistically significant, $U = 428$, $p = .74$ (low vision group, *M* = 5.40, *SD* = 0.44; sighted group, *M* = 5.51, *SD* = 0.31). However, the analysis did reveal a statistically significant effect of SANDPAPER, $\chi^2(2) = 35.32$, $p < .001$. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was also applied and so all effects were reported at a .02 level of significance. Wilcoxon tests found that the perceived roughness at 120 grit, 320 grit, and 400 grit sandpaper samples were statistically significantly different from each other ($p < .02$). The sample medians are displayed in Figure 44 (for 120 grit, *Mdn* = 5.70; for 320 grit, *Mdn* = 5.52; for 400 grit, *Mdn* = 5.22).

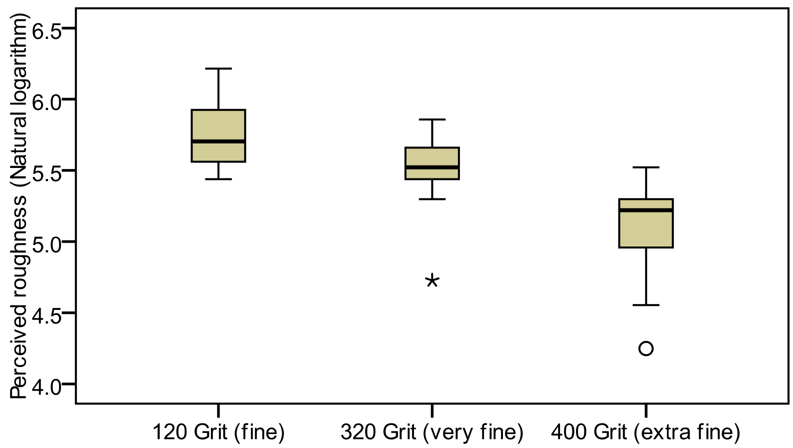


Figure 44. The perceived intensity of physical stimuli (Fine, Very Fine, and Extra Fine) ($p < .02$)

3.3. Discussion

3.3.1. Age-related individual-difference study

The age-related individual-difference study examined the extent to which younger and older users with low vision share a common perception of the same objective stimulus. As stated earlier in the literature review, although both younger and older people with low vision share the same disability category, older adults additionally tend to experience age-related sensory degeneration. In particular, changes occur in the sense of touch, leading to limited haptic sensory inputs. According to brain plastic theory, such deficient sensory inputs are likely to affect older adults' brain plastic change, ultimately influencing their haptic performance. Thus, the present study had anticipated that the perceived intensity of older participants with low vision would be different from their younger counterparts when the same objective intensity was present. However, the results of this research showed that the perception of the same objective stimulus was not significantly different between younger and older participants with low vision.

It is well known that when a sensory modality is damaged, brain plastic changes occur and continue with age (Mora, Segovia, & del Arco, 2007). In fact, the duration of vision loss was not significantly different between the two age groups of participants in the present research, $t(18)=1.07$, $p = .30$. It can therefore be assumed that there was not a statistically significant difference with regard to the period of experiencing brain plastic changes. It can be viewed that both groups shared approximately the same degree of brain plastic changes and enhancement of haptic perception. Based on this argument above, it should not be surprising that similar haptic perceptions were observed in the two age groups.

However, Mora and his colleagues (2007) stated that the degree to which the brain reorganizes its structure indeed varies at different ages; that is, greater changes were observed in younger individuals than in their older counterparts. Given those researchers' result, despite the same duration of vision loss, greater brain plastic change would be typically expected in the younger group than the older group. Based on the logic above, younger participants with low vision in Study 1 were still anticipated to show a significantly different haptic perception compared to their older counterparts in the magnitude estimation test. However, the present research found additional factors that could possibly explain why younger participants with low vision did not show a significantly different haptic perception compared to their older counterparts: (a) the onset of vision loss and (b) the level of expertise in a haptic-related task. A more detailed explanation of the two factors follows.

First, the two age groups had slightly different vision conditions in terms of the onset of visual impairment, which might affect brain plastic changes and mental models leading to such a nonsignificant difference. On average, younger participants in the present study had their vision impaired at 5.3 years of age while older participants experienced their vision loss at 60.3 years of age. More specifically, eight (80%) of all younger participants experienced their vision loss at or before the age of 7, which is a critical period in which one's visual imagery and mental model construction are significantly influenced (Jastrow, 1880). Furthermore, six (60%) of all younger participants with low vision were visually impaired from birth. While younger participants in the present study were considered a congenital or early-onset visual impairment group, older participants were considered a late-onset visual impairment group. Indeed, many prior researchers (Hannan, 2006; Hatwell et al., 2003) have pointed out that the onset of vision loss affects the degree of brain plasticity and capability in the remaining modalities of people with visual impairment. For instance, Marmor and Zaback (1976) empirically witnessed that individuals with early-onset visual impairment took longer and made more errors than those with late-onset visual impairment when performing a mental rotation test with 3D objects. The same mental rotation test was also conducted by including individuals with congenital visual impairment and late-onset visual impairment (Kerr, 1983). Those who were visually impaired from birth took longer compared to participants with late-onset visual impairment. These previous experimental studies provided valuable insight into a possible interpretation of the nonsignificant difference between the two age groups. Although the age factor might help younger participants have significant haptic perceptions, their early-onset vision loss possibly interfered with the younger group's performance. Based on all discussions above, it is possible to expect that haptic performance of younger individuals with low vision (early-onset) would not be significantly different from their older counterparts (late-onset) despite age differences.

Second, in addition to the onset of vision loss, level of expertise in certain tasks associated with a sense of touch might also influence younger participants' brain plastic changes and performance. Dulin (2007) explored the relationship of participants' performance with various levels of expertise in raised line materials. "Expert" participants who were visually impaired from birth outperformed "non-experts" with early- and late-onset visual impairment. Additionally, "expert" participants with early-onset visual impairment outperformed "non-expert" participants with late-onset visual impairment. Consequently, it is possible that a high level of expertise in a certain task is one of the critical attributes driving brain plasticity with positive outcomes. Indeed, both age groups in the present research were large print readers. None of the participants in this present study was a Braille reader. Hence, they can be considered "non-experts" who had a low level of expertise in raised line materials. In other words, there was no particular event (e.g., training for reading Braille) that served to enhance a participant's haptic capability through brain plasticity before the experiment. Thus, it can be interpreted that the degree to which the structure of the brain changed was not enough to invoke a significant enhancement of younger participants' haptic perception. In addition, older participants with low vision in the present research were a group who actively engaged in cognitively and physically stimulating activities, such as computer classes, local community meetings, and regular exercises. Such an enriched environment typically helps elderly people defend against negative physical, sensory, and cognitive aspects of aging (Mahncke et al., 2006; Wilson et al., 2003), which might also contribute to such nonsignificant difference between the two age groups.

On the other hand, there is also a possibility that brain plastic changes indeed occur to older participants, and the older adults possess the enhanced haptic capability. In fact, this research did not pay attention to older participants' prior occupations and hobbies (e.g., playing musical instruments or any other leisure activities related to the intensive use of touch modality) when developing the user profile. If older participants had been involved in such physically intensive activities related to a sense of touch, there is the likelihood that their brain plasticity changes occurred and were enough to invoke a significant enhancement of haptic perception, leading to no significant difference between older and younger participants.

Based on all arguments above, the framework in the literature review chapter was accordingly modified by adding new attributes: duration, onset, level of expertise in a haptic task, and enriched environment (see Figure 45).

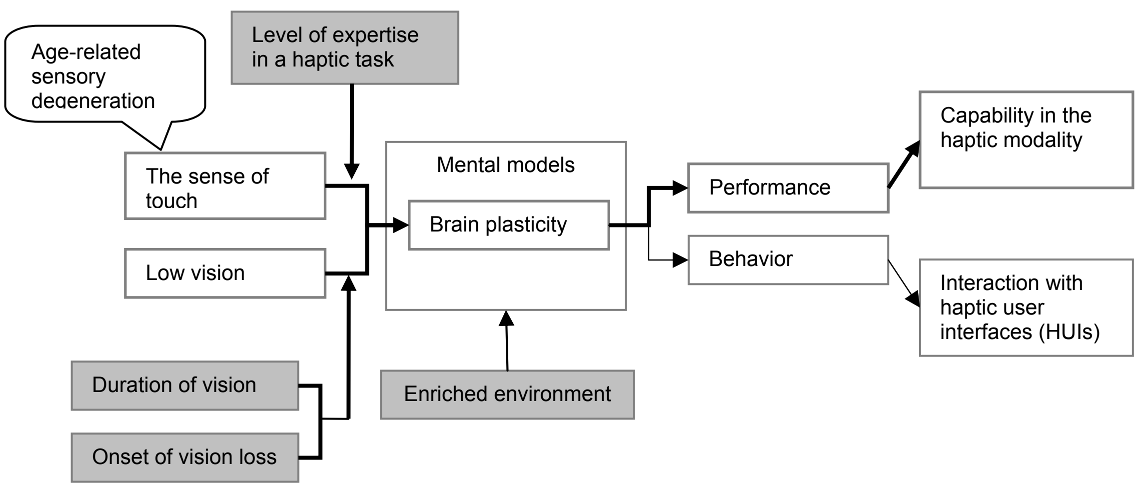


Figure 45. A revised framework for understanding capability in the haptic modality between younger and older individuals with low vision

The present research concerned aging effects in exploring individual differences of people with the same disability category, especially low vision rather than total blindness. Most prior studies on aging merely paid attention to individual differences between younger individuals *without* visual impairment and older people *without* visual impairment. The elderly population is expected to increase but is also likely to be influenced by age-related visual degeneration. As assistive technology advances, new types of user interfaces such as haptics may be introduced. It is not difficult to view older adults as one of the target user groups. The present study took the elderly with low vision into account to investigate the degree to which they share a common perception of the same haptic stimulus compared to their younger counterparts with low vision. In addition, a framework was introduced to help understand how younger and older individuals with low vision interact with the world, particularly related to haptic tasks.

Ideally, brain-imaging technology such as fMRI should be used to understand the relationship between specific cortices of the brain and the function they serve when individuals with low vision perform a task associated with the sense of touch. However, such equipment was not available for the present study. In general, such equipment and facilities are located at a medical school, and they are quite expensive to purchase for the present study. This lack of accessibility is likely to limit this research. However, as argued in the literature review section, the effectiveness of imaging technology remains doubtful, especially for an individual who becomes familiar with a certain task (Martin, 2006). For instance, certain novel stimuli generate activation, but repeating such stimuli generally leads to a decrease in neural activity (Yi et al., 2006). As a result, imaging technology tends to show inconsistent results. Alternatively, the present study used a magnitude estimation technique to measure the extent to which the sense of touch is enhanced in people with low vision. In fact, this technique was often used by many researchers to understand a participant's sensitivity, particularly related to the sense of touch (Gescheider, 1997; Jednorog et al., 2008).

Another weakness is that additional attributes (i.e., duration, onset, level of expertise in a haptic task, and enriched environment) influencing the present study were not considered while developing the initial framework. However, as shown in Figure 45, the initial framework was updated accordingly.

In addition, the stimuli (e.g., 120, 320, and 400 grits of sandpaper samples) might be too noticeable for both groups of participants leading to the non-significant difference, which is referred to as a ceiling effect. In that regard, sandpaper samples of super fine (e.g., 800 and 1000 grits) might be more suitable.

In contrast with the hypothesis proposed by the present research, the results showed no significant difference between the two age groups with low vision. Based on the result, haptic user interface designers can develop a haptic system with a certain range of force feedback magnitude (e.g., frequency of vibration) that is applicable to both younger and older users with low vision. Thus, an inclusive design approach becomes more feasible when associated with force feedback UI designs.

In addition, the results of magnitude estimation tests provided insight into the enhancement of accessibility of today's design methods for participants with visual impairment. More specifically, three texture samples (i.e., 120 grit sandpaper [Fine], 320 grit sandpaper [Very Fine], 400 grit sandpaper [Extra Fine]) were used in developing a modified PICTIVE design method. The roughness of all three texture samples was revealed to be distinctive enough for individuals with low vision to differentiate them. By applying the result, the three differently perceived sandpapers were used to help participants easily distinguish prototype artifacts. For instance, the 400 grit sandpaper was attached to a prototype widget (e.g., small paper box) that served as a certain user interface component (e.g., button) while the 120 grit sandpaper was used for another prototype widget that functioned differently. The two prototype widgets were perceived as different when participants with visual impairment touched them. Such enriched design environments contribute to participants' understanding of future system interfaces and promote participants engaging in design activities more actively.

Future research could include individuals with total blindness in order to compare their haptic modality to those with low vision. Haptic user interface designers can, thus, take into account the totally blind group's haptic capability in facilitating inclusive design of haptic technology. In addition, future research could include middle-aged adults with low vision who are between the ages of 30 and 65. The brain weight of an individual at the age of 30 generally begins decreasing causing neuronal degeneration, while people at the age of 65 enter a period of life of significantly declining haptic capability. For the middle-age user groups, the model (see Figure 45) in the present study should be modified to include new factors, such as brain weight and neuronal degeneration. In addition, a future study could be conducted including a greater variety of sandpaper samples to learn which samples are distinctive enough such that more various meanings can be assigned to those sandpaper samples and prototype widgets. In addition, the two factors (i.e., level of experience in a haptic task and onset of vision loss) should also be considered to investigate how they influence the two age groups differently in terms of their haptic capabilities.

3.3.2. Vision-related individual-difference study

The vision-related individual-difference study examined the extent to which users with different vision conditions (i.e., low vision and intact vision) shared a common perception of the same objective stimulus. As speculated in the literature review section, the sighted group and low vision group had different visual conditions, which would accordingly affect the two groups' brain plasticity and mental models differently. Thus, it was anticipated that haptic capabilities between the two vision groups would be different. However, the results showed that the perception of the same objective stimulus was not significantly different between the two vision groups.

This section is devoted to a discussion concerning why no significant difference was observed between the two vision groups. In particular, two factors were considered to explain the result of no significant difference: (a) visual modality contribution and (b) brain plastic changes. In general, in contrast with the low vision group, the sighted group must take advantage of their vision modality so the two vision groups would produce different results in magnitude estimation tests because sandpaper samples were not blinded. However, Kleiner et al. (1987) studied the influence of a sense of vision on human performance in an inspection task (e.g., inspecting steel cylinders for surface defects by feeling the surface with a metal probe); they found there was no effect of with and without vision among inspectors. Their empirical study supports the present research that vision does not contribute to performance in a task of tactile detection. Furthermore, Heller (1989) reported interesting research results that the visual modality does not significantly contribute to estimating the roughness of soft sandpaper samples. Heller empirically explored the relation between vision and texture perception. The results of Heller's study indicated that visual imagery is not crucial in a magnitude estimation task for soft textures (e.g., sandpaper grit 40 to 1000). He pointed out that visual modality would significantly contribute to the perception of rough textural features. In fact, texture samples that were used in the present research were soft, including 120 (Fine), 320 (Very Fine), and 400 (Extra Fine) grit sandpapers. Those soft samples are not distinctive enough to be differentiated through vision. Therefore, a sense of touch might be more engaged in the magnitude estimation tests than a sense of vision for both vision groups.

However, the touch modality of participants with low vision might not significantly be enhanced through brain plastic changes because of their low level of expertise in a haptic task. It has been shown that a level of expertise in a haptic-related task is likely to influence the brain plastic change and performance. In Dulin's study (2007), individuals with a higher level of expertise in raised line materials outperformed non-experts regardless of visual status, such as congenital blindness, early-onset blindness, and late-onset blindness. In addition to individuals with disability, those without disability are also somewhat affected by the level of expertise and brain reorganization mechanism. For instance, recent research (Mullan, 2000) has observed that long, repetitive activities (e.g., driving and navigation tasks) induced plasticity in the human brain structures. Mullan's study invited both 50 individuals who did not drive taxis and 16 taxi drivers to a brain examination (i.e., investigation of density of grey matter of the human brain). The taxi drivers had been driving for 14.3 years on average. The mean age and the age range did not differ between the taxi drivers and non-taxi drivers. The results showed that the taxi drivers had significantly larger posterior hippocampi, which are linked with navigation activities. The increase in the posterior hippocampal area was closely related to time spent driving and navigating.

Furthermore, repeated exposure to an environmental stimulus can trigger brain plastic change. Violin players, for instance, have stronger and more distinct representations of the fingers in the right hemisphere (Mahncke et al., 2006). Those empirical studies support a notion that the touch modality of sighted people is also correlated with the brain reorganization mechanism; however, brain plasticity with such positive outcomes generally requires an individual to engage in demanding ongoing sensory, cognitive, and motor activities on an intensive basis. Indeed, neither the sighted group nor the low vision group in the present study included Braille readers. In particular, those in the low vision group tended to rely on their residual vision in their daily life, which may have reduced their expertise level in raised line materials. In other words, there was no particular event that enhanced the two vision groups' haptic capabilities via brain plasticity before they participated in the magnitude estimation experiments. Thus, it can be considered that the degree to which the structure of the brain changed was not enough to result in significant enhancement of haptic perception. The level of experience related to tactile tasks was low. As a result, it becomes more understandable that the two vision groups showed no significant difference in terms of haptic perception.

Based on the arguments above, the initial framework proposed by the present study was updated to include level of expertise in a haptic task (see Figure 46). This vision-related individual-difference study can, hence, be supported by the updated framework. If those with total blindness were engaged, different results would be obtained because they are likely to rely on Braille to obtain information in their everyday life and could be viewed as experts. More significant brain plastic changes might occur in them, and increased connectivity between different brain lobes could positively influence their haptic capability.

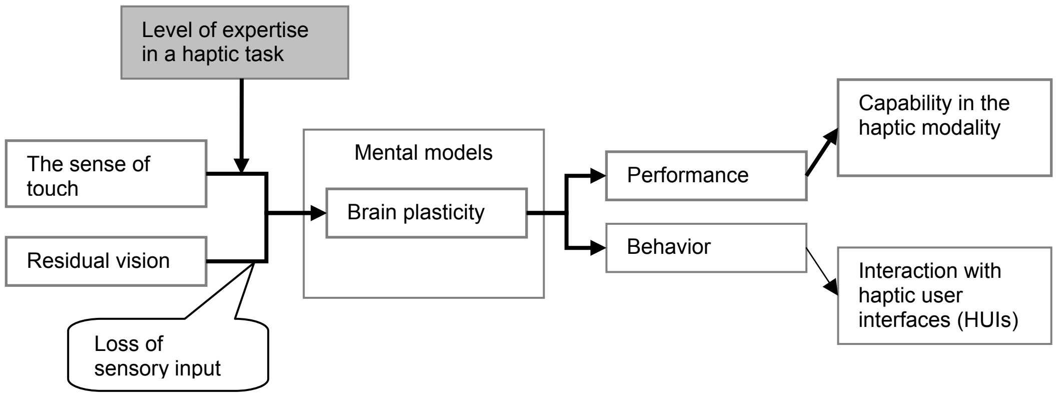


Figure 46. A revised framework understanding capability in the haptic modality of participants with low vision influenced by a level of expertise in a haptic task

The present research encountered challenges in recruiting participants for both the age- and vision-related individual-difference studies. While older participants lived together in a retirement community village in a local area, younger groups did not live in such a centralized residential area. In general, a school was thought to be a logical location where it would be relatively easy to find participants; however, it turned out that none of the students with visual impairment at Virginia Tech, Radford University, and New River Valley Community College responded to the request. Thus, the recruiting process took longer than expected. However, the low level of their interest was understandable because they might not want to expose themselves as one with disability. Because participants with low vision were not likely to drive, experiments were conducted at participants' locations, such as their residences and certain places convenient to them. Consequently, each experiment was accomplished under slightly different environments in terms of the time of day, air temperature, humidity, and lighting. However, such environments helped the researcher to conduct tests in real-world work settings in which participants' everyday living occurs. In general, a highly controlled laboratory experiment is likely to make participants nervous and alter their subjective estimation of the samples' roughness. The present research also attempted to control such an extraneous variable as human brain change in weight. Thus, the present research did not invite middle-aged adults with low vision (i.e., between the ages of 30 [the period of life when the human brain begins decreasing in weight, resulting in neuronal degeneration] and 65 [the period of life when significantly declining capability in the touch modality is observed]). In addition, the sandpaper samples (i.e., 120, 320, and 400 grits) might be too distinguishable for both groups of participants, leading to the non-significant difference. In that regard, sandpaper samples of super fine (e.g., 800 and 1000 grits) might be more suitable.

The results indicated no significant difference between sighted participants and those with low vision in terms of haptic capability. Based on the results, haptic user interface designers could take into consideration that a certain range of magnitude of haptic feedback is available to accommodate preferences of both user groups with low vision and sight. Doing so would increase the likelihood of successfully developing inclusive designs.

In addition, the present research results provided insight into enhancement of today's design procedures to increase accessibility for participants with visual impairment in a participatory design. In the original PICTIVE design, sighted designers were able to see the prototypes and obtain relevant information while participants who are visually impaired were unable to do so. As the original PICTIVE method uses different colors to distinguish and assign different meanings to design objects, the modified PICTIVE can make use of different textures to do so. The modified PICTIVE can resolve unequal accessibility issues. The roughness of all three texture samples (i.e., 120 grit sandpaper [Fine], 320 grit sandpaper [Very Fine], 400 grit [Extra Fine]) was found to be distinctive enough, and the three differently perceived sandpapers could be used in modifying the PICTIVE design method. For instance, the 400 grit sandpaper can be attached to a prototype widget (e.g., small paper box) that serves as a certain user interface component (e.g., button) while the 120 grit sandpaper would be used for another prototype widget that functions differently. The two prototype widgets would be considered different when participants with low vision touch them. Therefore, participants with low vision in the modified PICTIVE design method were able to obtain relevant information on design developments by touch. Such enriched design environments could enhance communication between participants with low vision and sighted designers and guide them to more dynamic design activities.

The results of this study can also be useful for a certain occupation such as human tactile inspection. The finding of no difference in haptic perception between sighted participants and those with low vision implies that people with low vision can also successfully accomplish the task of tactile inspection. A company should be encouraged to consider hiring people with low vision as well. In addition, the finding of the sandpaper effect implies that people have haptic perception to distinguish different tactile surfaces between 120 and 400 grits. Yet, it is recommended that a sensor device or an instrument be used to investigate materials with extra fine textures (e.g., above 400 grits), which can also be reflected on developing a job manual. Such a recommendation can enhance safety issues when the tactile inspection task is, for example, related to the detection of ice on aircraft surfaces.

Many prior researchers merely compared the haptic modality of individuals with *blindness* to that of sighted individuals. Thus, this research explored the haptic modality of individuals with *low vision* and that of sighted individuals. Yet, there is a need to compare the haptic modality between those with low vision and those with blindness. According to the model proposed by the present study (see Figure 46), the two groups with different visual conditions are likely to have different brain plastic changes and haptic capabilities. If it turns out that there is a significant difference between the two groups in terms of haptic capability, future research should be followed to investigate their HUI user needs.

3.3.3. Use of differently perceived sandpaper samples in study 2

Given the finding of participants' different perceptions related to different textures (sandpaper 120 grit, 320 grit, and 400 grit), these sandpaper samples were attached to prototype artifacts so that participants were easily able to recognize prototype artifacts. In addition, as already discussed in the literature review, several theoretical perspectives (e.g., Lederman & Klatzky's [1987] model of haptic exploratory procedures and Millar's [1994] spatial coding) were also consulted in modifying the original PICTIVE method. As a result, a modified PICTIVE design approach was developed and used in Study 2.

CHAPTER 4. STUDY 2: USER NEEDS ELICITATION METHOD

Study 2 included (1) a design method study (original PICTIVE versus modified PICTIVE) and (2) a documentation of HUI user needs, discussed in sections 4.1-4.3 and sections 4.4 -4.6, respectively. The HUI user needs were identified while conducting the design method study and were then used in Study 3.

4.1. Method

The primary objective of study 2 was to investigate the effectiveness of the modified PICTIVE design method.

4.1.1. Experimental design

The independent variables were the design methods (i.e., the modified PICTIVE and original PICTIVE). The dependent variable was participants' feedback on the use of an assigned method (see Table 18). Two independent samples (i.e., between-subjects design) were employed in Study 2 (see Table 19). An identical number of participants (n = 10) were assigned to each design method.

Table 18. Independent and dependent variables

Variable	Component
Independents Variables	Design method (the modified PICTIVE and original PICTIVE)
Dependent Variable	Participants' feedback on the use of the design method

4.1.2. Participants

The dominant opinion is that a usability study with a large number of participants does not generate significantly more information than a study with fewer participants (Spool & Schroeder, 2001). In fact, numerous researchers in Human Factors and HCI domains often employ only four or five participants. It has been reported that four or five participants are sufficient to identify approximately 80% of usability issues (Nielsen, 1998; Virzi et al., 1996). The recommendation to use four or five participants is also applicable to studies involving users who have visual impairment (Jones et al., 2005). In this research, a main task of participants with visual impairment was to identify what they like most and least about the design method. Given the aforementioned discussions, in total, twenty individuals with low vision (i.e., 10 younger and 10 older participants) were invited to participate in Study 2. A group of five younger and five older participants were randomly assigned to the modified PICTIVE and another group of five younger and five older participants were randomly assigned to the original PICTIVE. Table 19 shows the characteristics of participants in Study 2.

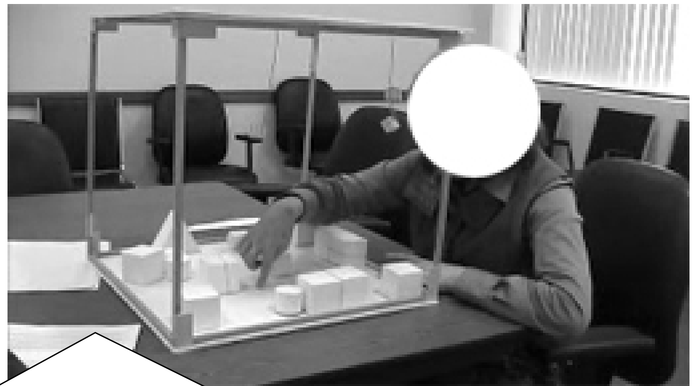
Table 19. The characteristics of participants in Study 2

	Modified PICTIVE	Original PICTIVE
Mean age (SD)	52.9 (32.87)	52.5 (32.02)
Mean age of onset of visual impairments (SD)	33.8 (31.39)	32.0 (33.13)
Mean duration of visual impairments (SD)	19.1 (15.02)	18.1 (13.35)
Mean visual acuity in decimal notation (SD)	0.16 (0.12)	0.17 (0.10)

The researcher served as the designer working along with participants in both the modified and original PICTIVE methods (henceforth referred to as “designer”). The designer had 7 years of hands-on experience conducting various Human Factors design methods, such as interviews, focus groups, observations (online and offline) and questionnaires. The designer had worked with a variety of participants, including secondary school students, college students, government officials, older adults (65+), and police officers. The designer had experience working with participants who have visual impairments.

4.1.3. Materials and equipment

Participants (i.e., users and the designer) in the original PICTIVE were given simple office supplies (e.g., paper-and-pencil, Post-it notes) as low-fidelity prototyping tools (Muller, 1991) (Figure 47, left). Participants assigned to the modified PICTIVE were given a collection of design objects that they were to manipulate during design sessions (Figure 47, right). The video camera was used to record design sessions and the voices of participants. It was unnecessary to hide the camera. The design objects fell into two categories. The first category was everyday office materials, such as a rubber band, thread, glue, sandpaper, a magnet, paper clips, adhesive tape, and thick paper. The second category included haptic widgets (small-sized boxes for interface components) that were prepared by the designer in advance. While the original PICTIVE used colored design artifacts, the modified PICTIVE used different textures. For example, different grits of sandpaper were attached to the surfaces of different sizes of boxes. In addition, there was a 3-D design space that was a cardboard box with a wooded frame (see Figure 47). The design space was referred to as the simulated virtual environment, which was originally represented by haptic technology. The “ceiling” of the design space allowed users and the designer to attach and hang a haptic widget, which was expected to improve participants’ sense of the 3-D environment. The sides of the design space were open to permit participants access for manipulating the design objects.



A collection of design objects
* Every-day office materials (e.g., a rubber band, thread, glue, sandpaper, magnet, paper clip, adhesive tape, and thick paper)

* Materials prepared by the designer to present multiple design exercises
  - Haptic widgets (e.g., small-sized cardboard boxes for interface components, e.g., buttons)
  - Several other tools to modify these items: scissors, glue, and adhesive tape

A design space in which prototyping activities are performed with design objects (e.g., 3-Dimensional design space that is made of think paper (a cardboard box with a wooden frame: The design space is referred to as an additional cue and a simulated virtual environment, which is originally represented by haptic technology. The "ceiling" of the box allows users and the designer to attach and hand a haptic widget, which is expected to improve participants' sense of the 3-D environment. The sides of the box are open to permit participants access to manipulate the design objects.)

A collection of design objects
* Every-day office materials (e.g., colored pens, highlighters, paper, Post-It notes of various sizes, stickers, labels, and paper clips)

* Materials prepared by the designer to present multiple design exercises
  - Icons (e.g., colored plastic icons for interface components)
  - Pop-up events (a suit of paper images)
  - Several other tools to modify these items: scissors, erasers, and pens

Figure 47. Design sessions of the modified PICTIVE (top) and the original PICTIVE (bottom)

Questionnaire: A questionnaire was prepared to facilitate the comparison of the modified PICTIVE to the original PICTIVE (see Figure 48). The format of the questionnaire was consistent with the set of design guidelines developed by Kaczmirek and Wolff (2007). This present research relied on Muller's assessment technique. When Muller developed the PICTIVE method, he also developed a questionnaire to demonstrate the usefulness of the PICTIVE method (Muller, 1992; Muller, 1993). More specifically, Muller's assessments consist of two types: quantitative assessments and qualitative assessments. In quantitative assessments, users were instructed to complete a 9-item questionnaire by reporting their opinions on the extent of their agreement with statements, such as "The design procedure helped me describe my job to the designers" and "The design procedure helped me to change the design to meet my needs." The rest of the statements included the following: "The procedure was enjoyable." "I am satisfied with this way of obtaining my input." "I believe that the people who were from the software product design group understood what I was trying to show them." "I am free to express myself." "The procedure was interesting." "The procedure was valuable." and "I hated being videotaped." The questionnaire was facilitated by a five-point Likert scale. It was assumed that the distance between each anchor was the same. In addition to the quantitative assessment, qualitative assessments were conducted by allowing users to answer an open-ended questionnaire item: "What was the best aspect of the procedure?" Thus, users could provide additional comments that were not covered by the quantitative assessment. Their comments were written down by the researcher or captured by a video camera. A full list of questions is presented in Appendix B. Participants chose one of various formats for the questionnaires, including a large print questionnaire and a computer-supported questionnaire.

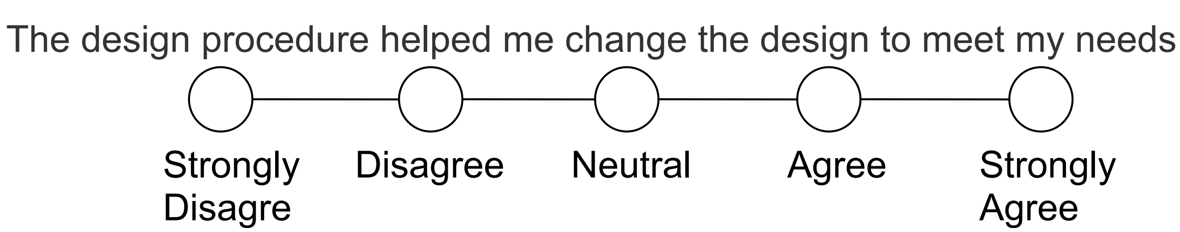


Figure 48. A sample question from the quantitative assessments

Each participant's vision acuity was measured using a Snellen chart. A participant was instructed to stand behind a line 20 feet from a wall-mounted Snellen vision chart. The participant covered one eye with an eye spoon and read aloud from the top line of letters (i.e., the largest letter) to the smallest line of letters that a participant can see. If a participant used the eye spoon, he or she was instructed not to apply pressure to the occluded eye because pressure can cause blurred vision and thus skew the results

(Haupt, 2008). This procedure was repeated for the other eye. The vision of each eye was recorded separately. The participant's vision acuity was represented by the acuity in the better eye with the best possible correction, according to the WHO classification of visual impairment.

4.1.4. Procedure

The procedure consisted of three steps: pre-design, design, and post-design, as shown in Figure 49. In the pre-design step, IRB informed consent forms, familiarity procedures, and vision check were completed. In the design step, a participant and the designer performed a design activity by participating in either the original PICTIVE method or the modified PICTIVE method. In the post-design step, a participant was instructed to provide feedback on the use of a given design method.

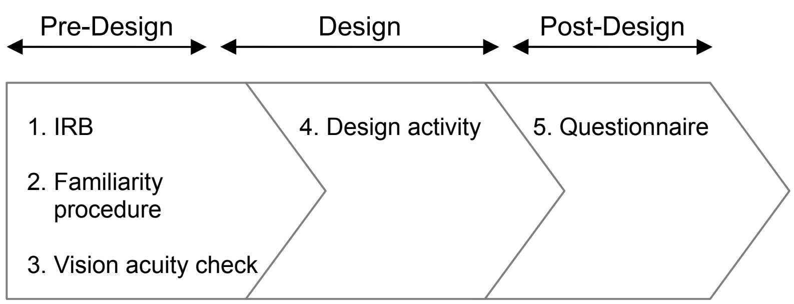


Figure 49. Design procedure

A participant was instructed to review the Virginia Tech IRB informed consent form and sign it. The informed consent form was available in various formats, including Braille and large print. A participant was given the informed consent form in his or her preferred format. The researcher indicated the location for the signature, if needed. A participant kept one copy of the informed consent form, but the other copy was kept by the researcher.

A participant was guided so he or she became familiar with the experimental equipment, procedures, and environments, such as the arrangement of chairs, desks, doors, and safety-related gadgets, if available. After a participant built mental images of the environment, the designer did not move anything without informing the participant. In addition, there were other considerations the designer needed to bear in mind: (a) explaining unusual noises and activities (e.g., clicking camcorder buttons, opening/shutting doors), (b) offering an elbow to lead the participant, (c) giving directions about where to be seated, (d) not interacting with a guide dog or service animal, and (e) telling the participant where there was a room for the guide dog. A short amount of time was assigned to a warm-up period, in which the participant and the designer shared personal information.

A Snellen vision chart was used to measure a participant's vision acuity in order to ensure that he or she fell into one of two categories: category 1 (moderate visual impairment) or category 2 (severe visual impairment).

Four fundamental design components associated with haptic user interfaces were introduced to a participant, including (a) navigation in the virtual environment, (b) finding objects and an overview, (c) understanding features of an object, and (d) discrimination of objects (Sjostrom, 2001b). As shown in Table 10, Table 11, Table 12, and Table 13, some situations were linked to fundamental design components, which were introduced to the participant. The participant was then instructed to think carefully about the situation and design haptic user interfaces accordingly. The participant's design ideas and any manipulation in the design space were captured on video recordings for further investigation.

The questionnaire (see Appendix B) was completed by the participant to obtain feedback on the assigned method (either original PICTIVE or modified PICTIVE). The participant was compensated at a rate of $10 per hour. In total, sessions lasted approximately 60 to 90 minutes.

4.1.5. Data analysis

The research question was "What is the most effective PICTIVE-based method to elicit needs of participants with visual impairment in designing haptic user interfaces?" Thus, this research sought to compare how participants in each design method (i.e., modified and original PICTIVE design methods) perform design activities. According to Olson, Olson, Carter, & Storrosten (1992), one way to compare groups is based on how groups work with their methods (e.g., object-oriented design methods) and supplemental resources (e.g., various design tools). For instance, Olson et al. focused on how design discussions unfold over time, what kinds of activities group members are involved in, how they orchestrate their activities, how designers use their time, and how similar these patterns are across different groups. It has also been known that measuring group members' comments and gestures helps to identify the degree to which members understand and/or agree with their presentation (Olson & Olson, 1993). In other words, those features imply the engagement of group members (Olson et al., 1993). In addition to comments and gestures, the amount of time spent on design activities has also been identified as a critical aspect in comparing different groups (Olson, Olson, Carter, & Storrosten, 1992). McLeod (1992) conducted a meta-analysis of numerous empirical studies that explored the relationships between group process, supporting tools, and outcomes. He found that many studies viewed “the time needed to complete a task” and “the satisfaction of group members” as important variables in comparing different groups. In addition, Pinsonneault and Kraemer (1989) introduced a theoretical framework to explain the relationship between group outcomes and resources by considering the context, the process, the task-related outcomes, and the group-related outcomes of group interaction. Particularly, the group-related outcomes include member’s satisfaction. Drawing on this body of previous research, the present study analyzed four categories of data: gestures, time spent on design activities, reported satisfaction, and frequency of users’ comments related to design ideas (see Table 20).

Table 20. Overview of data analyses to compare two design methods

Objective data	Gesture	Time spent on design activities
Subjective data	Frequency of users’ comments related to design ideas	Users’ self-rated satisfaction

Participants’ gestures were investigated to compare the degree to which participants in the two design methods contributed to design activities. Gestures serve as a critical means to obtain attention and to express ideas (Bekker, Olson, & Olson, 1995). For example, participants in design processes use gestures to articulate their design idea, simulate its use, and emphasize their verbalized design ideas (Bekker et al., 1995). Sharkey et al. (2000) empirically observed that participants with visual impairment also use gestures to express ideas. They consciously or unconsciously transmit messages to others by moving their hands and fingers. Recent research (Frame, 2000) has reported that individuals with visual impairment felt less uncomfortable with the use of gestures while speaking compared to sighted people. Furthermore, gesture is regarded as one of the prominent attributes of design activities. Tang and Leifer (1988), for instance, studied a small group design session to understand collaborative workspace activity.

In particular, the researchers counted the frequency of sighted participants' use of hands and arms. They reported that 65% of the gestures were associated with the actions of drawing graphs and making a list, and 35% were used to refer to an object in the workspace or enact simulations. In general, people are apt to develop a misconception that those who have lost vision are less likely to use visual cues (e.g., gestures) in communication because they cannot see. However, Frame (2000) empirically observed gestural activities among participants with visual impairment (including those with low vision and total blindness). In general, it is known that gestures serve various communicative functions in design activities. For example, gestures are used in characterizing a certain design aspect, describing its use, emphasizing ideas, referring to persons, showing distances, and communicating about design ideas in many other ways (Bekker et al., 1995).

McNeill's theory (2005) indicates that there are two types of thinking influencing both gestures and speech. One is imagistic thinking, which is characterized as global and synthetic, while the other is syntactic thinking, which is viewed as linear and segmented (see Figure 50). In particular, imagistic thinking is considered to be the determining process contributing to the production of gestures: a gesture delivers a meaning as a whole rather than as a separated unite (e.g., speech). In addition, Blass et al. (1974) empirically studied the gestural activity of individuals with visual impairment, and claimed that body movements make two contributions to communication: (a) intrapersonally, body movements serve to convert thoughts into words, and (b) interpersonally, body movements serve to deliver information to listeners and affect listeners' behaviors.

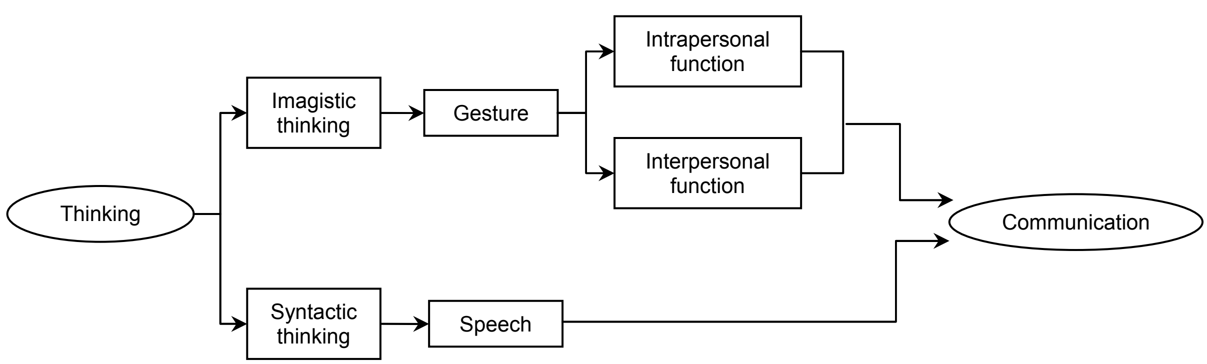


Figure 50. A schema of relations between thinking and communication

A lack of gesture is likely to reduce the amount of information that speakers can deliver and listeners can receive. If there is, however, an increase in the use of gesture, it means that imagistic thinking is facilitated. Sharkey and Asamoto (2000) also pointed out that people with a higher frequency of gestures are regarded as being deeply interested and actively involved in ongoing conversations. Therefore, an understanding of gestures offers insight into the degree to which participants in the two design methods exchanged ideas and contributed to design activities.

As discussed in the literature review section, the original PICTIVE design method was modified to increase accessibility. The modified PICTIVE design method could provide participants with tangible haptic widgets. As a result, participants were expected to result in obtaining enriched information with regard to the design activities. Such an enriched design environment might boost the degree to which participants understand, become involved in, and become interested in the design activities. In other words, their thinking process might be facilitated, which will positively affect the imagistic thinking and gestures. In addition, participants' syntactic thinking and speech might be influenced as well. In short, incorporation of haptic prototype widgets in design processes might facilitate participants' gestures and speech. Furthermore, such an enriched information and understanding about ongoing design activities might contribute to participants' satisfaction. Participants who are not confused about design tasks can be expected to produce more design ideas and spend more time contributing to the design activities compared to participants with less understanding.

Participants' comments: The modified PICTIVE was compared with the original PICTIVE by exploring the frequency of participants' comments related to design ideas. Participants' verbal feedback (i.e., qualitative data) was captured by a video camera during design activities; then, the frequency of comments (i.e., quantitative data) was compared between the two design groups. In other words, comparing the two design methods (i.e., the original and modified PICTIVE methods) was accomplished by conducting a statistical analysis of qualitative data. The data (i.e., frequency of participants' comments) were obtained through a content analysis (Krippendorff, 1980; Stemler, 2001). According to the guidelines of Krippendorff, absolute frequencies (e.g., the numbers of incidents found in a sample group) were calculated. The statistical analysis of qualitative data has been known to be acceptable and useful

(Alasuutari, 1995; Kaplowitz, 2000; Krippendorff, 1980; Tohidi, Buxton, Baecker, & Sellen, 2006). Qualitative researchers successfully incorporated statistics in their qualitative analysis by computing cross-tabulations, presenting tables, and counting cases (Alasuutari, 1995; Kaplowitz, 2000). For example, Kaplowitz (2000) and Tohidi (2006) relied on *t*-tests, *Chi-square* tests, and frequencies to compare two design methods (i.e., individual interviews and focus groups) by using users' statements. Tohidi's study (2006) was similar to the present study and gave insight on the data analysis. More specifically, Tohidi's study compared a set of different prototyping techniques for the design of a touch-sensitive screen. His study aimed to assess the effectiveness of different types of design techniques based on users' verbal feedback. They classified users' feedback in the following groups: positive comments, negative comments, superficial suggestions, and substantial suggestions. Thus, the present research employed the classified categories in analyzing the participants' statements. Tohidi et al. used a two-tailed *t*-test to compare different prototyping techniques based on the number of users' statements. By considering prior studies' data analysis approaches, the present study also extended the usefulness of statistical approaches to qualitative data analysis.

The Shapiro-Wilk tests were performed to check the normality of the data. The results revealed that the data were normal (original PICTIVE, $W = .97$, $p = .86$; modified PICTIVE, $W = .96$, $p = .82$). Therefore, the frequency of users' statements derived by the two design methods was analyzed using an independent-samples *t*-test. A statistical analysis was performed on a dependent variable with $\alpha \leq .05$ to test whether there was a significant difference between participants using the modified PICTIVE and the original PICTIVE with respect to the number of users' statements. The independent variable was a method type. The dependent variable was the overall number of users' statements. The statistical analysis was conducted with the assumption of homogeneity of variance, and it was facilitated by SAS™ software version 8.2. The following alternative hypothesis was considered:

- The frequency of users' statements will differ between those using the original PICTIVE and those using the modified PICTIVE.

Gestures: Participants' gestures were analyzed using a gesture analysis technique. Many researchers have used the gesture analysis technique to understand how actively people in a face-to-face design team contributed to design activities by means of gestures (Bekker et al., 1995; Frame, 2000; Tang & Leifer, 1988). The gesture analysis technique is typically focused on the investigation of how frequently an individual uses gestures for certain purposes in design processes (see Table 21) (Bekker et al., 1995; Tang et al., 1988). More specifically, the present research referred to the following scholars' studies on communicative gestures: Bekker (1995), Frame (2000), and Lederman (1987).

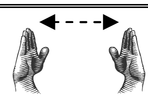
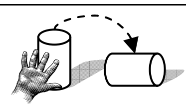
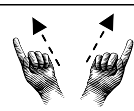
First, Bekker and his colleagues (1995) presented a list of gesture "purposes" in design activity. Bekker and his colleagues developed the list of gesture purposes under the assumption that participants would be sighted and able to manage information by writing on paper or a whiteboard. The present research, therefore, excluded part of Bekker's list that was related to the activity of written information management because participants in the present study had visual impairment. In addition, Bekker's list missed certain purposes of gesture, such as to "contrast *places"* and "refer to *ideas"* although Bekker's list included "refer to *places"* and "contrast *ideas"*. Such missing purposes were added to the list for the present study.

Second, Frame (2000) presented a list of gesture types. However, Frame's list included certain types of gestures that were difficult to apply directly to the present research, so Frame's list was also appropriately modified. For instance, the movement of arms, hands, or fingers not serving any apparent communicative function was considered in Frame's list and was indexed as an adaptor (e.g., scratching an itchy spot). Because the present research was more interested in the relation between gestures and communication in design activities, adaptors were excluded. Furthermore, some types of gestures were combined due to their similarity. For example, according to Frame, both conservational gestures and topic gestures were regarded as any movement of the arms, hands, or fingers that served some communicative function.

Besides the lists of Bekker (1995) and Frame (2000), Lederman's exploratory procedure list (1987) also contained a series of hand or finger movement patterns that were observed among individuals in attempting to understand objects: such patterns include lateral motion, pressure, static contact, unsupported holding, enclosure, and contour following. Thus, the exploratory procedures were also considered in conducting the gesture analysis. In addition to understanding *material* properties, understanding *spatial* properties also plays a critical role in perceiving and discriminating locations of haptic prototype widgets in design activities. The following gesture types were also included: (a) enacting the interaction between an individual and an artifact (e.g., relocation of an artifact) and (b) describing (or drawing) something on a table with the fingers.

Appendix C offers a matrix that includes a full list of gesture purposes and gesture types with detailed descriptions. The frequency of gestures was calculated by using the matrix in Appendix C (Bekker et al., 1995; Tang et al., 1988). Table 21 shows a sample; for example, the purposes of gestures include "show sizes" and "contrast two or more design ideas" (Bekker et al., 1995). The types of gestures include "beat series" and "topic gestures" (Frame, 2000).

Table 21. A sample matrix indicating the purposes for which each type of gesture is used

Purpose of gesture in design activity	Type of gesture		Frequency
	Beat series	Topic gestures	
Show sizes 			
Enact the interaction between a user and a product 			
Contrast two or more ideas 			

The Shapiro-Wilk tests were performed to check the normality of the data. The results revealed that the data were normal (original PICTIVE, $W = .96$, $p = .82$; modified PICTIVE, $W = .88$, $p = .12$). Therefore, the number of gestures derived by the two design methods was analyzed using an independent-samples *t*-test. More specifically, an independent-samples *t*-test was performed on a dependent variable with $\alpha \leq .05$ to test whether there was a difference between people with low vision using the modified PICTIVE and people with low vision using the original PICTIVE with respect to the number of gestures. The independent variable was a method type. The dependent variable was the number of gestures. The independent-samples *t*-test was conducted with the assumption of homogeneity of variance. The statistical analysis was facilitated by SAS™ software version 8.2. The following alternative hypothesis was considered:

- The frequency of users' gestures will be different between participants in the original PICTIVE and those in the modified PICTIVE.

Self-rated satisfaction: Participants completed a Likert scale questionnaire, which determined the extent to which they were satisfied with the original PICTIVE or the modified PICTIVE. Cumulative scores indicated each participant's overall agreement with the ratings they assigned to nine items on the questionnaire (see Appendix B).

The Shapiro-Wilk tests were performed to check the normality of the data. The results revealed that the data were normal (original PICTIVE, $W = .93$, $p = .42$; modified PICTIVE, $W = .86$, $p = .07$). Therefore, user rating scores were analyzed using an independent-samples *t*-test. More specifically, an independent-samples *t*-test was performed on a dependent variable with $\alpha \leq .05$ to test whether there was a difference between people with low vision using the modified PICTIVE and people with low vision using the original PICTIVE with respect to their satisfaction. The independent variable was a method type. The dependent variable was the cumulative scores on the questionnaire. In addition, the score for individual questions was explored. The independent-samples t-test was conducted with the assumption of homogeneity of variance. The statistical analysis was facilitated by SAS™ software version 8.2. The following alternative hypothesis was considered:

- Users' self-rated satisfaction will be different between participants in the original PICTIVE and those in the modified PICTIVE.

Time: The duration of design tasks was measured to compare the two design methods. Multimodal critical path analysis (CPA) was conducted to assess the duration of design tasks. In fact, CPA has been extensively used in the domain of project management to seek the longest series of activities in a project, thereby determining the earliest completion route and/or time for a project. Human Factors engineers adopted CPA and used it for a number of purposes, including a design development process, a performance evaluation, and a performance prediction (Stanton, Salmon, Walker, Baber, & Jenkins, 2005). In addition to the multimodal CPA, a keystroke level model (KLM) method is also often used to calculate response times; however, KLM assumes that all tasks are performed in series instead of parallel

(Stanton et al., 2005). The KLM method is inappropriate for the present study because participants used multiple sensory modalities (e.g., haptic, auditory, long-term memory, and somewhat impaired vision), and these different sensory channels were engaged in a design task in parallel. Participants with low vision can feel an object, see displays, and hear sound simultaneously.

Multimodal CPA was accomplished by following a detailed protocol addressed by Stanton (2005). It consisted of a total of six steps: (a) analyze the tasks to be modeled, (b) order the tasks, (c) allocate sub-tasks according to modality, (d) sequence the subtasks in a multimodal CPA diagram, (e) allocate time to the subtasks, and (f) determine the time to perform the whole task.

The Shapiro-Wilk tests were performed to check the normality of the data (original PICTIVE, $W = .99$, $p = .99$; modified PICTIVE, $W = .93$, $p = .41$). The results revealed that the data were normal. The duration of design tasks derived from the two design methods was analyzed using an independent-samples *t*-test. The independent variable was a method type. The dependent variable was the duration of design tasks. More specifically, an independent-samples *t*-test was performed on a dependent variable with $\alpha \leq .05$ to test whether there was a difference between people with low vision using the modified PICTIVE and the original PICTIVE in terms of the duration of design tasks. The independent-samples *t*-test was conducted with the assumption of homogeneity of variance. The statistical analysis was facilitated by SAS™ software version 8.2. The following alternative hypothesis was considered:

- The duration of design tasks will be different between participants in the original PICTIVE and those in the modified PICTIVE.

4.2. Results

4.2.1. Statement

Research Question: What is the most effective PICTIVE-based method to elicit the needs of participants with visual impairment in designing haptic user interfaces?

H_a: The frequency of users' statements will differ between those using the original PICTIVE and those using the modified PICTIVE.

The frequency of participants' statements were analyzed using an independent-samples *t*-test, after verification that the data were normal (original PICTIVE, $W = .97$, $p = .86$; modified PICTIVE, $W = .96$, $p = .82$). This analysis revealed a significant difference between the two design groups, $t(18) = -4.91$; $p < .05$. The sample means are displayed in Figure 51, which shows that participants in the modified PICTIVE had a significantly higher number of statements than did participants in the original PICTIVE (for original PICTIVE method group, $M = 30.00$, $SD = 4.37$; for modified PICTIVE method group, $M = 42.20$, $SD = 6.53$).

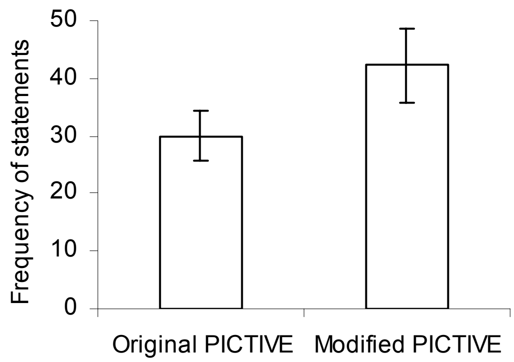


Figure 51. Frequency of participants' statements (*p* < .05)

As shown in Figure 52 and Figure 53, positive comments made up the largest segment and accounted for 47% of participants' statements in the original PICTIVE while substantial suggestions were the largest segment and accounted for 55% of participants' statements in the modified PICTIVE.

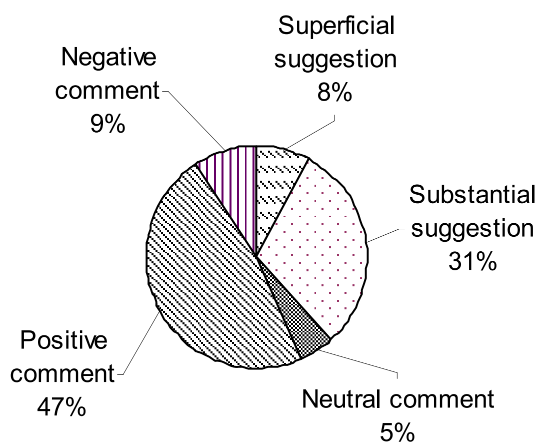


Figure 52. The distribution of participants' statements in the original PICTIVE design method

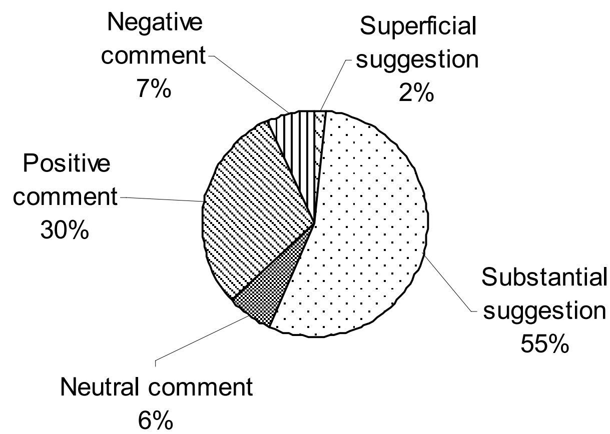


Figure 53. The distribution of participants' statements in the modified PICTIVE design method

4.2.2. Gesture

Research Question: What is the most effective PICTIVE-based method to elicit the needs of participants with visual impairment in designing haptic user interfaces?

H_a: The frequency of users' gestures will be different between participants in the original PICTIVE and those in the modified PICTIVE.

Participants' gestures were analyzed by calculating the frequency of gestures. In addition, each gesture was categorized by type and purpose. The results of this analysis are presented in two parts: (a) coders' data analyses including interrater reliability tests (in section 4.2.2.1.) and (b) the data analyses (in section 4.2.2.2.).

<u>4.2.2.1. Results of coders' data analysis</u>

a. Overall frequency of gesture

It is well known that a reliability check is best conducted by a stratified sampling design (Krippendorff, 1980). Therefore, to determine reliability, this research divided participants into two groups according to gender and selected a simple random sample from each group. It is also recommended not to use all data but a sample of data for a reliability test (Krippendorff, 1980). Furthermore, according to the standards and guidelines for the calculation and reporting of intercoder reliability (Lombard, Snyder-Duch, & Bracken, 2002), the appropriate sample size should be at least 10% of the full sample. As a result, the present research chose three individuals from the modified PICTIVE design method group and another three individuals from the original PICTIVE design method group (one female and two male individuals in each design method group).

Given the recommendation of Krippendorff (1980), coders were engaged in the reliability check and instructed to perform the same procedure of the gesture data analysis. In total, three coders were initially engaged. In the end, two coders' data were taken to run the reliability test. Coders were students at Virginia Tech and had no prior experience with conducting Human Factors experiments. Two coders were given introductions as to how to code gestures under the same condition, such as training time, coding sheet, and definition of variables to be coded.

In particular, the present research relied on the intraclass correlation coefficient (ICC) to explore the reliability of this gesture study. In fact, a number of statistical methods are available to enable the calculation of a reliability index. In contrast to other methods, the ICC provides various forms, each of which can be applied to specific situations defined by the aim of a study and its experimental designs. Thus, by applying an appropriate ICC form, a more accurate reliability test can be performed.

To compute intraclass correlation coefficients, the present research used INTRACC.SAS macro, which was obtained from the online library of SAS Institute, Inc. The macro was developed based on the formulas of well-known scholars Shrout and Fleiss (1979) and Winder (1971). The INTRACC.SAS macro generated three different cases, including six indices: case I [ICC (1, 1), ICC (1, 2)], case II [ICC (2, 1), ICC (2, 2)], case III [ICC (3, 1), and ICC (3, 2)]. Based on the guidelines by Shrout and Fleiss (1979), the present research attempted to obtain the second case, ICC II. Case II is based on a two-way random effects model. Not only are the coding targets considered random, but the coders are also deemed a random effect. However, today's scholars hold contradictory views as to which type of index should be used: absolute agreement type or consistency type. Bartko (1976) claimed that the consistency type was inappropriate. Instead, he suggested that content analysts use the absolute agreement type. On the other hand, Algina (1978) disagreed with Bartko's theory and argued that coders (also called raters) should be regarded as fixed effects. Afterward, Bartko (1978) avoided directly responding to Algina's argument, but he readdressed his earlier position once again. Thus, the present research indentified both types of reliability index below:

Absolute agreement type	ICC = .61
Consistency type	ICC = .71

With regard to the acceptable value for the reliability coefficient, many researchers still argue, and there is no universally accepted set of criteria. For example, Cohen (1988) suggested the following criteria: .1 is small effect size, .3 is medium effect size, and .5 is large effect size. On the other hand, Lombard et al. (2002) reviewed rules of thumb set out by several methodologists, and reported that "coefficients of .9 or greater are nearly always acceptable, .8 or greater is acceptable in most situations, and .7 may be appropriate in some exploratory studies" (Lombard et al., 2002, p. 700). However, Lombard et al. stated that much lower criteria could also be acceptable unless a percent agreement method (i.e., liberal index) was used for a reliability check. However, Krippendorff, a well-known content analyst, provided insight into the establishment of a meaningful level of reliability: "standards for data reliability must be related to the validity requirements imposed upon research results, specifically to the costs of drawing wrong conclusions" (Krippendorff, 1980, p. 147). For instance, if a study is related to a person's life and death, a content analyst should be very careful to accept a standard for data reliability because a content analyst's decision might result in a situation in which a person is killed in a car accident. Because the present research is less associated with a person's life and death, lower criteria can be used in interpreting the reliability test results.

Given the aforementioned argument on the absence of a universally acceptable level of reliability and the present research's choice of no liberal index, the values .6 and .7 of ICC can be regarded as acceptable.

Based on the data analysis of two coders, the means of gesture frequency in both design methods are displayed in Figure 54. On average, the frequency of gestures in the modified PICTIVE (Coder 1, *M* = 145.70, *SD* = 74.30; Coder 2, *M* = 220.70, *SD* = 114.90) was higher than the original PICTIVE method (Coder 1, *M* = 29.30, *SD* = 19.35; Coder 2, *M* = 83.30, *SD* = 77.90), which is consistent with the results of the data analysis.

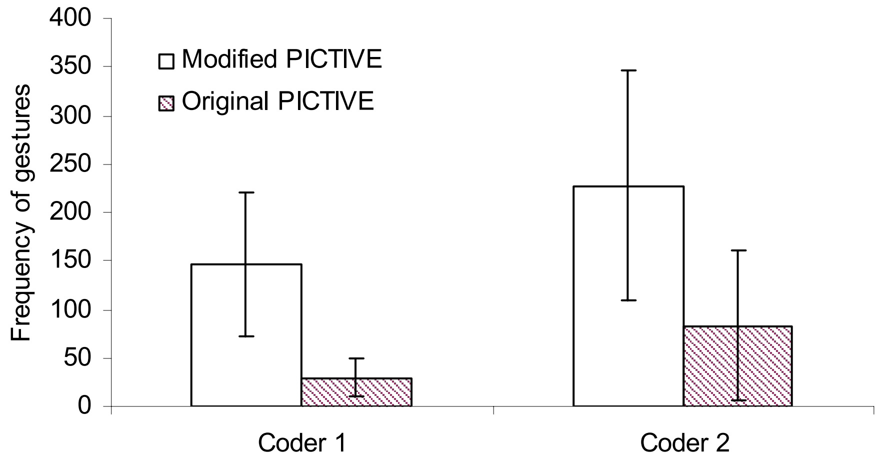


Figure 54. Frequency of gestures found by two coders with regard to two design methods

b. Gesture type

In the previous reliability calculation, ICC was used to explore the overall amount of gesture frequency, which was indeed appropriate because ICC is known to be able to handle the magnitude of data. However, in the data analysis on the gesture type category (and also gesture purpose category), Pearson product-moment correlation coefficient (sometimes referred to as the PMCC and typically denoted by *r*) can be used instead. As mentioned earlier, the primary aim was to establish the order in which gesture types would be ranked according to the frequency of gesture type observed in each design method. PMCC enables investigation of interrater reliability with regard to ranked data.

The results showed a strong correlation coefficient (r = .7) between two coders' analyses of gesture types in the *modified* PICTIVE; thus, the reliability is acceptable. The descriptive statistics are shown in Table 22.

Table 22. Frequency of gesture types in the modified PICTIVE between two coders

	Modified PICTIVE					
Category of gesture type	Coder 1			Coder 2		
	Mean	SD	%	Mean	SD	%
Beat (touch)	2.30	2.10	1.60%	10.00	12.20	4.40%
Beat (untouched)	1.30	2.30	0.92%	6.30	7.80	2.79%
Beat series (untouched)	1.30	1.50	0.92%	1.30	0.60	0.59%
Beat series (touch)	0.00	0.00	0.00%	0.70	0.60	0.29%
Contour following	0.00	0.00	0.00%	18.70	9.10	8.21%
Drawing line with finger	1.30	1.50	0.92%	0.00	0.00	0.00%
Enclosure	0.00	0.00	0.00%	27.00	18.70	11.88%
Finger-to-body	1.30	1.20	0.92%	3.00	3.60	1.32%
Finger-to-finger	0.70	0.60	0.46%	0.30	0.60	0.15%
Finger-to-hand movement	0.00	0.00	0.00%	0.00	0.00	0.00%
Lateral motion	2.70	2.30	1.83%	8.70	5.50	3.81%
Pointing	19.30	20.50	13.27%	10.30	12.70	4.55%
Pressure	0.30	0.60	0.23%	2.00	2.60	0.88%
Relocation of an object	8.00	10.60	5.49%	21.00	32.90	9.24%
Static contact	43.00	32.80	29.52%	8.70	3.50	3.81%
Emblem	10.30	17.90	7.09%	2.70	3.80	1.17%
Topic gesture (depictive)	48.30	46.40	33.18%	106.30	55.00	46.77%
Unsupported holding	5.30	4.90	3.66%	0.30	0.60	0.15%
Sum			100%			100%

Note. Three participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture type

Another interrater reliability was explored with regard to two coders' analyses of gesture types in the *original* PICTIVE. The results showed a strong correlation coefficient (r = .9). Therefore, the reliability is acceptable. The descriptive statistics are shown in Table 23.

Table 23. Frequency of gesture types in the original PICTIVE between two coders

	Original PICTIVE					
Category of gesture type	Coder 1			Coder 2		
	Mean	SD	**%**	Mean	SD	**%**
Beat (touch)	1.00	1.00	3.41%	6.70	4.00	8.00%
Beat (untouched)	0.00	0.00	0.00%	2.00	2.60	2.40%
Beat series (untouched)	0.00	0.00	0.00%	0.00	0.00	0.00%
Beat series (touch)	0.00	0.00	0.00%	0.00	0.00	0.00%
Contour following	0.00	0.00	0.00%	0.70	0.60	0.80%
Drawing line with finger	0.00	0.00	0.00%	1.70	1.50	2.00%
Enclosure	0.00	0.00	0.00%	0.00	0.00	0.00%
Finger-to-body	0.30	0.60	1.14%	1.00	1.00	1.20%
Finger-to-finger	0.00	0.00	0.00%	1.00	1.70	1.20%
Finger-to-hand movement	0.30	0.60	1.14%	0.30	0.60	0.40%
Lateral motion	2.00	1.00	6.82%	4.70	5.50	5.60%
Pointing	4.00	4.40	13.64%	9.70	10.00	11.60%
Pressure	0.00	0.00	0.00%	0.30	0.60	0.40%
Relocation of an object	0.00	0.00	0.00%	1.00	1.00	1.20%
Static contact	5.30	5.50	18.18%	1.00	1.70	1.20%
Emblem	1.30	1.20	4.55%	0.00	0.00	0.00%
Topic gesture (depictive)	14.70	13.30	50.00%	53.00	58.60	63.60%
Unsupported holding	0.30	0.60	1.14%	0.30	0.60	0.40%
Sum			100%			100%

Note. Three participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture type

The analysis results of coder 1 and coder 2 are addressed in the following sections respectively. However, it should be noted that, while the main data analysis invited 10 participants for each design group, each coder analyzed the gestures of only three participants per design group. Thus, coders' gesture categorizations could differ from the main data analysis results.

Data analysis of coder 1: Depictive gesture (33.18%) was the most frequently used type in the modified PICTIVE, which was consistent with the analysis results. Besides the depictive gesture, the following gesture types were frequently used: static contact (29.52%), pointing (13.27%), emblem (7.09%), and relocation of an object (5.49%). The use of other gesture types was below 5%. The depictive gesture was also the most frequently used type in the original PICTIVE; however, the degree to which depictive gesture contributed to the original PICTIVE (50%) was higher compared to its use in the modified PICTIVE (33.18%), a finding that is also consistent with the analysis results. Besides the depictive gesture, participants in the original PICTIVE largely relied on static contact (18.18%), pointing (13.64%), and lateral motion (6.82%). The use of other gesture types was below 5%.

Data analysis of coder 2: Coder 2 also had similar results. Depictive gesture (46.77%) was the most frequently observed type in the modified PICTIVE, followed by enclosure (11.88%), relocation of an object (9.24%), and contour following (8.21%). The depictive gesture was also the most frequently used gesture type in the original PICTIVE (63.6%). However, participants in the original PICTIVE relied more on the depictive gesture than did those in the modified PICTIVE. Besides the depictive gesture, pointing (11.6%) and beat-touch (8%) were frequently used in the original PICTIVE. The use of other gesture types was below 5%.

c. Gesture purpose

The primary aim of the gesture purpose analysis was to learn which gesture purpose was the most frequently used and contributed the most to the design activity. Pearson product-moment correlation coefficient helped to investigate interrater reliability with regard to ranked data. The results showed a weak correlation coefficient (*r* = .13) between the two coders' analyses of gesture purposes in the modified PICTIVE. The descriptive statistics are shown in Table 24.

Table 24. The frequency of gesture purpose in modified PICTIVE between two coders

Category of gesture purpose	Modified PICTIVE					
	Coder 1			Coder 2		
	Mean	SD	%	Mean	SD	%
contrast ideas	1.67	1.53	1.14%	5.00	5.29	2.20%
contrast objects	0.00	0.00	0.00%	8.67	7.37	3.81%
contrast persons	0.33	0.58	0.23%	2.00	1.00	0.88%
contrast places	0.67	1.15	0.46%	11.00	9.64	4.84%
depict performance	22.33	12.58	15.33%	19.67	10.12	8.65%
highlight idea	0.67	0.58	0.46%	70.00	56.43	30.79%
list items	0.00	0.00	0.00%	1.00	0.00	0.44%
refer to a body part	0.67	1.15	0.46%	0.67	1.15	0.29%
refer to idea	64.33	20.03	44.16%	4.00	2.65	1.76%
refer to object	11.33	9.24	7.78%	22.33	18.23	9.82%
refer to person	1.67	2.89	1.14%	7.67	8.96	3.37%
refer to places	11.67	10.21	8.01%	16.33	9.02	7.18%
show distance	0.33	0.58	0.23%	1.67	1.15	0.73%
show shapes	0.00	0.00	0.00%	4.00	2.00	1.76%
show sizes	1.00	1.00	0.69%	1.00	1.00	0.44%
understand object	29.00	31.76	19.91%	52.33	15.31	23.02%
Sum			100%			100%

Note. Three participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture purpose

Another interrater reliability was explored with regard to two coders' analyses of gesture purposes in the original PICTIVE. The results showed a weak correlation coefficient (*r* = .34). The descriptive statistics are shown in Table 25.

Table 25. The frequency of gesture purpose in original PICTIVE between two coders

Category of gesture purpose	Original PICTIVE					
	Coder 1			Coder 2		
	Mean	SD	%	Mean	SD	%
contrast ideas	1.67	2.08	5.68%	5.67	8.08	6.80%
contrast objects	4.00	6.08	13.64%	1.33	2.31	1.60%
contrast persons	1.33	1.15	4.55%	0.67	1.15	0.80%
contrast places	6.33	10.12	21.59%	4.00	6.08	4.80%
depict performance	3.00	2.65	10.23%	17.33	23.18	20.80%
highlight idea	8.00	13.00	27.27%	14.00	4.58	16.80%
list items	1.00	1.00	3.41%	1.33	2.31	1.60%
refer to a body part	2.33	3.21	7.95%	0.00	0.00	0.00%
refer to idea	1.00	1.73	3.41%	2.33	4.04	2.80%
refer to object	0.67	1.15	2.27%	9.67	14.22	11.60%
refer to person	0.00	0.00	0.00%	2.33	2.52	2.80%
refer to places	0.00	0.00	0.00%	5.33	5.03	6.40%
show distance	0.00	0.00	0.00%	10.67	18.48	12.80%
show shapes	0.00	0.00	0.00%	3.33	4.16	4.00%
show sizes	0.00	0.00	0.00%	4.33	5.86	5.20%
understand object	0.00	0.00	0.00%	1.00	1.00	1.20%
Sum			100%			100%

Note. Three participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture purpose

The analysis results of coder 1 and coder 2 are addressed in the following sections respectively. However, it should be noted that, while the main data analysis invited 10 participants for each design group, each coder analyzed the gestures of only three participants per design group. Thus, coders' gesture categorizations could differ from the main data analysis results.

Data analysis of coder 1: While participants in the modified PICTIVE used nearly 50% of their gestures to refer to design ideas, those in the original PICTIVE used only 3.41% of their gestures to refer to design ideas. Such different patterns were also observed in other gesture purpose categories, for example, understanding an object (modified, 19.91%; original, 0%), referring to places (modified, 8.01%; original, 0%), and referring to an object (modified, 7.78%; original 2.27%). In addition, the frequently used gesture purposes in the original PICTIVE were rarely used in the modified PICTIVE, such as to highlight an idea (modified, 0.46%; original, 27.27%), contrast places (modified, 0.46%; original, 21.59%), contrast objects (modified, 0%; original, 13.64%), refer to a body part (modified, 0.46%; original, 7.95%), and contrast ideas (modified, 1.14%; original 5.68%). In particular, the analysis of the results also indicated that the gesture purpose of understanding an object was rarely used in the original PICTIVE (modified, 11.66%; original 0%), which is consistent with coder 1's analysis result.

Data analysis of coder 2: To highlight an idea (30.79%) was the most frequently used gesture purpose in the modified PICTIVE, followed by understanding an object (23.02%), referring to an object (9.82%), depicting performance (8.65%), and referring to places (7.18%). Use of the others was below 5%. On the other hand, participants in the original PICTIVE generally used their gestures in order to depict performance (20.80%), highlight an idea (16.80%), show distance (12.80%), and refer to an object (11.60%). To understand an object was one of the frequently used gesture purposes in the modified PICTIVE; however, the same purpose was less observed in the original PICTIVE, with only 1.2% usage. Instead, participants in the original PICTIVE used their gestures more frequently in order to depict performance instead of to understand an object, a result that is consistent with the analysis result.

As compared to the gesture categorization by type, gesture categorization by purpose was more influenced by subjective decisions made by coders, which might have led to the lower value of the reliability index. In fact, the category of gesture types consisted of distinctive, physical movements such as beat series, enclosure, lateral motion, and pressure such that coders might be less confused in terms of distinguishing gesture types. As a result, there was less deviation between two coders' data analysis results. In contrast, there was a lack of physical, objective clues to identify participants' intentions in using gestures. Therefore, the task of categorizing gestures by purpose probably required coders' subjective interpretation, which may have led to more diverse results in data analyses between two coders (i.e., a lower value of reliability index).

4.2.2.2. Results of the data analysis

a. Overall frequency of gestures

Gestures were analyzed using an independent-samples *t*-test, after verification that the data were normal (original PICTIVE, $W = .96$, $p = .82$; modified PICTIVE, $W = .88$, $p = .12$). This analysis revealed a significant difference between two design methods, $t(18) = 3.08$; $p < .05$. Mean values of gesture frequency in the two design methods are displayed in Figure 55, which shows that participants in the modified PICTIVE made a significantly higher number of gestures than did participants in the original PICTIVE (for original PICTIVE method group, $M = 54.20$, $SD = 30.61$; for modified PICTIVE method group, $M = 128.60$, $SD = 69.88$).

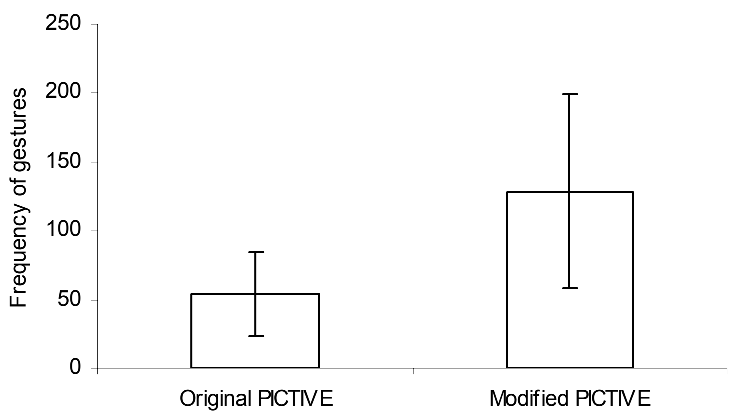


Figure 55. Frequency of participants' gestures in the modified and original PICTIVE methods (*p* < .05)

b. Gesture type

When the frequency of gesture was counted, gestures were also categorized by gesture type as a further analysis. The aim was to investigate which gesture type was the most frequently used in each design method. The raw data (i.e., the frequency of gesture in each gesture type category) were converted into percentages. Table 26 shows the descriptive statistics for gesture types.

Table 26. Frequency of gesture types in original and modified PICTIVE methods

Category of gesture type	Modified PICTIVE			Original PICTIVE		
	Mean	SD	%	Mean	SD	%
Beat (touch)	0.00	0.00	0.00%	0.60	1.26	1.11%
Beat (untouched)	0.00	0.00	0.00%	0.40	1.26	0.74%
Beat series (touch)	4.00	4.27	3.11%	1.50	1.84	2.77%
Beat series (untouched)	0.00	0.00	0.00%	0.00	0.00	0.00%
Contour following	3.00	4.11	2.33%	0.40	0.84	0.74%
Drawing line with finger	1.20	2.57	0.93%	1.20	1.40	2.21%
Enclosure	9.30	12.99	7.23%	0.60	0.84	1.11%
Finger-to-body	1.20	1.23	0.93%	0.50	0.71	0.92%
Finger-to-finger	0.50	0.85	0.39%	1.20	2.30	2.21%
Finger-to-hand movement	0.00	0.00	0.00%	0.00	0.00	0.00%
Lateral motion	11.20	7.84	8.71%	1.50	1.08	2.77%
Pointing	4.10	5.36	3.19%	4.50	8.87	8.30%
Pressure	2.70	3.02	2.10%	0.90	1.45	1.66%
Relocation of an object	6.90	15.42	5.37%	0.00	0.00	0.00%
Static contact	7.40	6.65	5.75%	0.50	1.27	0.92%
Stereotypical hand signal (emblem)	0.40	0.97	0.31%	0.00	0.00	0.00%
Topic gesture (depictive)	73.70	29.47	57.31%	39.70	29.45	73.25%
Unsupported holding	3.00	2.00	2.33%	0.70	1.06	1.29%
Sum			100%			100%

Note. Ten participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture type

In the modified PICTIVE, depictive gesture (i.e., one that is related to conversation topic without using any physical artifact) was the most frequently used gesture type (57.3%), followed by lateral motion (8.7%), enclosure (7.2%), static contact (5.8%), and relocation (5.4%). The degree to which the other gesture types contributed was below 5%.

In the original PICTIVE, depictive gesture (73.25%) was also the most frequently used gesture type. However, the percentage data between two design groups showed that participants in the original PICTIVE (73.25%) more relied on the depictive gesture than did those in the modified PICTIVE (57.3%). On the other hand, gesture types related to interaction with physical artifacts were less frequently used by those in the original PICTIVE, for example, lateral motion (2.77%), enclosure (1.11%), static contact (0.92%), and relocation of an object (0%).

c. Gesture purpose

After the frequency of gestures was counted, gestures were also categorized by gesture purpose as a further analysis. The purpose was to investigate which gesture purpose was used the most frequently in each design method. That is, the degree to which each gesture purpose contributed to a design method was compared. The raw data (i.e., the frequency of gesture in each gesture purpose category) were converted into percentage data. Table 27 shows the descriptive statistics of gesture purposes.

Table 27. Frequency of gesture purpose in original and modified PICTIVE

Category of gesture	Modified PICTIVE			Original PICTIVE		
purpose	Mean	SD	**%**	Mean	SD	**%**
contrast ideas	2.00	3.60	1.56%	0.70	0.95	1.29%
contrast objects	2.80	3.70	2.18%	0.50	0.97	0.92%
contrast persons	0.20	0.40	0.16%	0.00	0.00	0.00%
contrast places	0.40	1.30	0.31%	0.30	0.48	0.55%
depict performance	16.50	9.50	12.83%	11.80	10.59	21.77%
understand an object	15.00	21.00	11.66%	0.00	0.00	0.00%
list items	3.50	3.80	2.72%	2.10	2.28	3.87%
refer to a body part	2.00	1.90	1.56%	0.80	2.20	1.48%
refer to an idea	6.30	4.20	4.90%	2.70	3.89	4.98%
refer to an object	38.90	32.00	30.25%	10.40	6.36	19.19%
refer to a person	8.40	11.00	6.53%	4.30	4.37	7.93%
refer to a place	11.10	10.00	8.63%	6.20	5.03	11.44%
show distance	1.70	1.40	1.32%	1.70	4.37	3.14%
show shapes	2.70	2.10	2.10%	2.40	1.96	4.43%
show sizes	2.90	1.70	2.26%	2.30	2.54	4.24%
highlight an idea	14.20	8.80	11.04%	8.00	5.03	14.76%
Sum			100%			100%

Note. Ten participants per design method group
Note. Appendix C includes detailed descriptions with regard to each gesture purpose

In the modified PICTIVE, the most frequently observed gesture purpose was to refer to an object (30.25%), followed by depicting performance (12.83%), understanding an object (11.66%), and highlighting an idea (11.04%). In the original PICTIVE, the most frequently used gesture purpose was to depict performance (21.77%), followed by referring to an object (19.19%), highlighting an idea (14.76%), and referring to a place (11.44%). Use of the other purposes was below 5%. Comparing the percentage data between the two design methods indicated that participants in the modified PICTIVE tended to use their gestures largely in order to refer to an object (e.g., prototype widgets of navigation buttons). However, those in the original PICTIVE used their gestures mostly in order to depict certain performance (e.g., the action of pretending to press a button). In addition, understanding an object was found to be one of the top three gesture purposes frequently observed in the modified PICTIVE, yet understanding an object was a gesture purpose that was never used in the original PICTIVE.

4.2.3. Self-rated satisfaction

Research Question: What is the most effective PICTIVE-based method to elicit the needs of participants with visual impairment in designing haptic user interfaces?

H_a: Users' self-rated satisfaction will be different between participants in the original PICTIVE and those in the modified PICTIVE.

Cronbach's alpha as the measure of internal consistency reliability: This research explored the internal consistency reliability of participants' responses to the questionnaire through Cronbach's alpha. Two groups of participants in the original and modified PICTIVE completed a questionnaire with nine questions (also called items), and alpha values were .55 (original PICTIVE) and .67 (modified PICTIVE). However, alpha values for both design groups increased when the ninth item was removed. More precisely, the alpha value for the original PICTIVE became .78, and the alpha value for the modified PICTIVE became .74. A Cronbach's alpha value over .7 is typically regarded as acceptable (Nunnally, 1978).

This research doubted that the ninth item was properly designed. In fact, the questionnaire was constructed by Muller (1991), who attempted to demonstrate the effectiveness of the original PICTIVE. All items (i.e., the first to eighth items) except the ninth item were designed to have favorable tone toward a given design method; for example, "Procedure helps me describe my job," "I am satisfied with this means of obtaining my input," and "I feel free to express myself." Yet, the ninth item was "I *hated* being videotaped." It was observed that some respondents made an attempt to confirm the meaning of the ninth item with the researcher, and certain respondents asked permission from the researcher to change their rating score on the ninth item even after their rating task was over. They stated that they misunderstood the meaning of the ninth item, considering it to be "I did NOT hate being videotaped." Such confusion was likely to cause certain respondents to misinterpret the ninth item, possibly leading to the lower internal consistency.

Cumulative scores for each participant's overall satisfaction: After the ninth item was deleted, the data analysis of participants' overall satisfaction was performed. Results were analyzed using a Mann-Whitney test, after verification that the data in the modified PICTIVE group were non-normal (original PICTIVE, $W = .95$, $p = .66$; modified PICTIVE, $W = .81$, $p = .02$). The analysis revealed no significant difference between the two groups, $U = 41.50$; $p = .53$ (original PICTIVE, $M = 36.10$, $SD = 2.60$; modified PICTIVE, $M = 35.60$, $SD = 3.17$).

Individual scores for each question: Statistical analyses were conducted for each item (item numbers 1 to 9). The Shapiro-Wilk tests were performed to check the normality of the data. The results revealed that the data were non-normal. Therefore, the Mann-Whitney test was chosen to analyze the data. All analyses revealed no significant difference between the two design groups in terms of satisfaction. The analysis results for each item are presented below.

<u>Item # 1: "The procedure helps me describe my job to the designer."</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .78$, $p = .01$; modified PICTIVE, $W = .78$. $p = .01$). This analysis revealed no significant difference between the two design groups, $U = 50.00$; $p = 1.00$ (original PICTIVE, $M = 4.40$, $SD = 0.70$; modified PICTIVE, $M = 4.40$, $SD = 0.70$).

<u>Item # 2: "The design procedure helps me change the design to meet my needs."</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .60$, $p < .001$; modified PICTIVE, $W = .78$. $p = .001$). This analysis revealed no significant difference between the two design groups, $U = 43.50$; $p = .63$ (original PICTIVE, $M = 4.30$, $SD = 0.48$; modified PICTIVE, $M = 4.40$, $SD = 0.69$).

<u>Item # 3: "I believe that the people who were from the software product design group understood what I was trying to show them."</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .54$, $p < .001$; modified PICTIVE, $W = .73$. $p = .003$). This analysis revealed no significant difference between the two design groups, $U = 38.00$; $p = .39$ (original PICTIVE, $M = 4.20$, $SD = 0.42$; modified PICTIVE, $M = 4.40$, $SD = 0.84$).

<u>Item # 4: “I feel free to express myself.”</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .60$, $p < .001$; modified PICTIVE, $W = .65$. $p < .001$). This analysis revealed no significant difference between the two design groups, $U = 48.50$; $p = .91$ (original PICTIVE, $M = 4.70$, $SD = 0.67$; modified PICTIVE, $M = 4.50$, $SD = 0.53$).

<u>Item # 5: “I am satisfied with this means of obtaining my input.”</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .80$, $p = .01$; modified PICTIVE, $W = .66$. $p < .001$). This analysis revealed no significant difference between the two design groups, $U = 42.50$; $p = .58$ (original PICTIVE, $M = 4.30$, $SD = 0.67$; modified PICTIVE, $M = 4.50$, $SD = 0.53$).

<u>Item # 6: “The procedure was enjoyable.”</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .51$, $p < .001$; modified PICTIVE, $W = .65$. $p < .001$). This analysis revealed no significant difference between the two design groups, $U = 40.00$; $p = .48$ (original PICTIVE, $M = 4.80$, $SD = 0.42$; modified PICTIVE, $M = 4.60$, $SD = 0.52$).

<u>Item # 7: “The procedure was interesting.”</u>

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .36$, $p < .001$; modified PICTIVE, $W = .65$. $p < .001$). This analysis revealed no significant difference between the two design groups, $U = 35.00$; $p = .28$ (original PICTIVE, $M = 4.90$, $SD = 0.32$; modified PICTIVE, $M = 4.60$, $SD = 0.52$).

Item # 8: "The procedure was valuable."

The data were analyzed using a Mann-Whitney test, after verification that the data were non-normal (original PICTIVE, $W = .66$, $p < .001$; modified PICTIVE, $W = .84$. $p = .04$). This analysis revealed no significant difference between the two design groups, $U = 35.00$; $p = .28$ (original PICTIVE, $M = 4.50$, $SD = 0.53$; modified PICTIVE, $M = 4.10$, $SD = 0.74$).

Item # 9: "I hated being videotaped."

The data were analyzed using a Mann-Whitney test, after verification that the data in the original PICTIVE were non-normal (original PICTIVE, $W = .51$, $p < .001$; modified PICTIVE, $W = .86$. $p = .07$). This analysis revealed no significant difference between the two design groups, $U = 36.00$; $p = .32$ (original PICTIVE, $M = 4.20$, $SD = 1.69$; modified PICTIVE, $M = 3.90$, $SD = 1.10$).

Item # 10: "What was the best aspect of the design activity?"

Both groups of participants in the original and modified PICTIVE were allowed to briefly state their impressions of the given design method. Few participants provided feedback on the design methods. Overall, both groups liked the given design method they used, as shown in Table 28 and Table 29. None of them provided negative feedback.

Table 28. Feedback from participants in the original PICTIVE design

	Participants' comments
Strength	*"It is only one design procedure; difficult to judge. But, the design procedures look straightforward."*
	"[The design activity] *caused me to think about something that was new and novel to me."*
Benefit from being involved in design developments	*"I learned some interesting things from the designer."*
	"I felt like I had a voice and that my disability is not a curse but an avenue to bring change."
Appreciation	*"Appreciated being able to put in my ideas, being able to put in my two cents worth."*
	"I appreciated being questioned by a sighted designer about this type of thing because sighted people do not always have the best understanding of what blind people need. I appreciate someone trying to see things my way."

Table 29. Feedback from participants in the modified PICTIVE design

	Participants' comments
Strength	*"I liked and preferred when I could manipulate the objects, as opposed to talking about it verbally in abstract form."*
	"The frame and haptic widgets are helpful to image or project the 3D space."
	"I like the idea of using different texture and small boxes."
	"Feeling different surfaces so as to identify."
Suggestion to improve	*"I would like to make the small boxes bigger."*
Benefits from being involved in design developments	*"It makes me think* [about] *my own situation: more being outside."*
	"I feel like I am very important."
Interaction with a designer	*"All of it, because I think I helped you* [designer] *all with aspect of designing and deploying these technology."*
	"The designer seemed enthusiastic, especially of my ideas."
	"Working with you [designer] *and sharing the excitement for this project."*

4.2.4. Time spent on design activities

Research Question: What is the most effective PICTIVE-based method to elicit the needs of participants with visual impairment in designing haptic user interfaces?

H_a: The duration of design tasks will be different between participants in the original PICTIVE and those in the modified PICTIVE.

A design task was accomplished through three phases: input, process, and output (see Figure 56). In the input phase, the designer introduced four design situations, including navigation, finding an object, understanding an object, and discriminating between two objects. After the introduction of each situation, the participant began working with a designer to develop haptic user interfaces. For instance, a participant was informed of design contexts related to the navigation in virtual environments (VE) and was asked a question "How should it be designed to facilitate user's navigation in V.E.?" In the output phase, a participant shared design ideas.

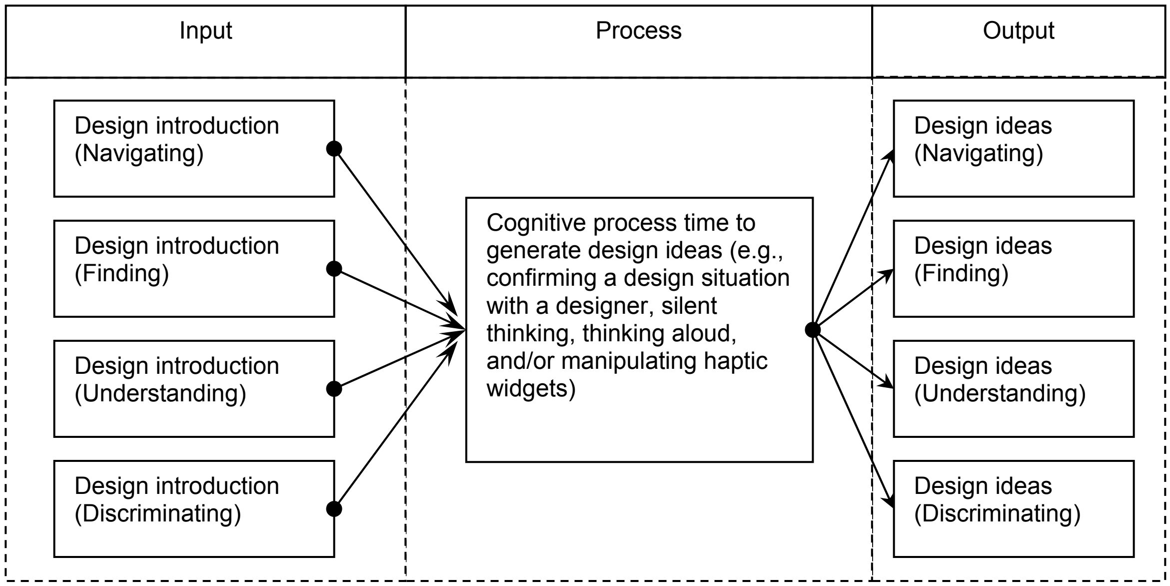


Figure 56. A task consists of input, process, and output

Input time was the duration of the designer's introduction. The measurement of process time began right after the designer's inquiry (e.g., "How should it be designed to facilitate user's navigation in V.E.?"), and the measurement continued until a participant began sharing a design idea. Afterward, the designer's follow-up questions were asked if needed. However, this post-hoc interview interaction was excluded from the data analysis because it tended to result in design ideas related to multiple design situations (navigating, finding, understanding, and discriminating) instead of a single entity. Isolating them and calculating the time for each design situation was not feasible.

<u>Overall time for input, process, and output</u>

The Shapiro-Wilk tests indicated that the data were normal (original PICTIVE, $W = .99$, $p = .99$; modified PICTIVE, $W = .93$, $p = .41$). Therefore, results were analyzed using an independent-samples *t*-test. This analysis revealed a significant difference between the two design groups, $t(18) = -4.74$; $p < .05$. The sample means are displayed in Figure 57, which shows that participants in the modified PICTIVE spent significantly more time than did participants in the original PICTIVE (for original PICTIVE method group, $M = 285.00$, $SD = 82.60$; for modified PICTIVE method group, $M = 454.70$, $SD = 77.30$).

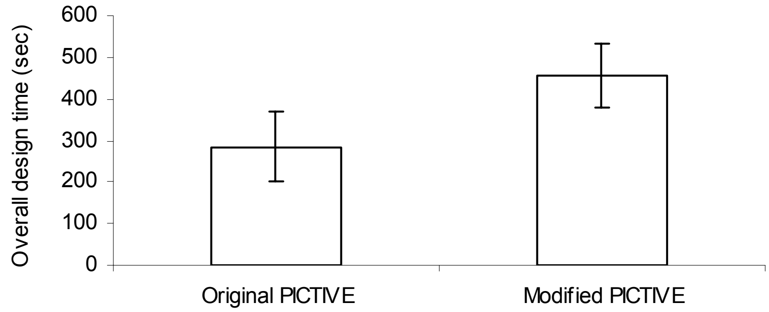


Figure 57. Overall design time in two design methods (*p* < .05)

Input time in design

The Shapiro-Wilk tests indicated that the data were normal (original PICTIVE, *W* = .91, *p* = .26; modified PICTIVE, *W* = .89, *p* = .17). Therefore, results were analyzed using an independent-samples *t*-test. This analysis revealed no significant difference between the two design groups (original PICTIVE, *M* = 149.8, *SD* = 19.70; modified PICTIVE, *M* = 198.3, *SD* = 19.70), *t*(18) = 1.74; *p* = .10.

Process time in design

The Shapiro-Wilk tests indicated that the data were normal (original PICTIVE, *W* = .91, *p* = .27; modified PICTIVE, *W* = .94, *p* = .53). Therefore, results were analyzed using an independent-samples *t*-test. This analysis revealed no significant difference between the two design groups (original PICTIVE, *M* = 68.80, *SD* = 44.84; modified PICTIVE, *M* = 91.70, *SD* = 58.10), *t*(18) = - 0.99; *p* = 0.34.

Output time in design

The Shapiro-Wilk tests indicated that the data were normal (original PICTIVE, *W* = .86, *p* = .07; modified PICTIVE, *W* = .94, *p* = .47). Therefore, results were analyzed using an independent-samples *t*-test. This analysis revealed a significant difference between the two design groups, *t*(18) = - 3.18; *p* < .05. The sample means are displayed in Figure 58, which shows that participants in the modified PICTIVE spent significantly more time collaborating with a designer to generate design ideas than did participants in the original PICTIVE (for original PICTIVE method group, *M* = 66.40, *SD* = 50.98; for modified PICTIVE method group, *M* = 164.70, *SD* = 83.49).

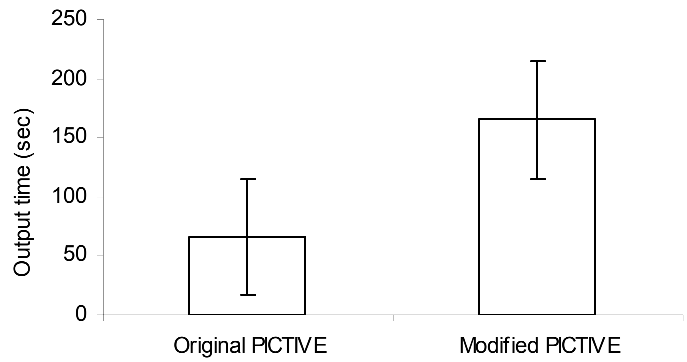


Figure 58. Output time in two design methods (*p* < .05)

4.3. Discussion

The research question addressed in Study 2 was "What is the most effective design method to elicit the needs of users with visual impairment in designing haptic user interfaces?" The original PICTIVE design method was modified and referred to as a modified PICTIVE. It was hypothesized that the two design methods would result in different outcomes in terms of the frequency of participants' statements, gestures, satisfaction, and time to complete a given design task. The following sections discuss data results for the four variables (i.e., statements, gestures, satisfaction, and time) and are followed by a summary discussion.

4.3.1. Statements

First, the frequency of participants' statements related to design ideas were counted. The results revealed that participants in the modified PICTIVE made a significantly higher number of statements than did participants in the original PICTIVE. Further investigations compared the two design methods by classifying the statements of each group of participants. To be more precise, almost half (47%) of the statements by participants in the original PICTIVE consisted of positive comments rather than others (i.e., negative comment, substantial suggestion, superficial suggestion, and substantial suggestion). The participants tended to be passive and simply agreed to ideas of a designer by stating, "Yes, I think so," "That's a good idea," or "That would be useful." On the other hand, participants in the modified PICTIVE generated largely substantial suggestions (55%) more than other types (i.e., negative comment, positive comment, superficial suggestion, and substantial suggestion). For instance, when a designer and a participant discussed how to design automatic movement of an input device (e.g., stylus) to help a user easily understand a 3D figure, a participant in the original PICTIVE merely stated that relying on such an automatic movement is a good idea. On the contrary, a participant in the modified PICTIVE offered more detailed design ideas, for example, suggesting that the automatic movement should be from the bottom up and then cross a 3D figure because such a series of movements is the way they usually locate or understand an object in real life. In general, participants in the modified PICTIVE tended to be more dynamic and creative in generating design ideas or insight.

4.3.2. Gestures

Another attempt was made to investigate the degree to which participants understand, get involved, and become interested in design activities by exploring the frequency of their gestures. It was postulated that the frequency of participants' gestures would be different between those using the original PICTIVE and the modified PICTIVE. In fact, participants in the modified PICTIVE showed a significantly higher number of gestures than did participants in the original PICTIVE.

Additional research attempts were made to examine two design groups' gesture type and gesture purpose. Participants in the original PICTIVE limited using their hands and arms to illustration of certain situations as opposed to physical interaction with prototype artifacts. Besides the illustration-type gesture, the other gesture types were generally not used in the original PICTIVE design group. On the contrary, relatively diverse gesture types were observed among participants in the modified PICTIVE; for example, they did hold objects (e.g., prototype widgets), relocate objects, and haptically explore objects (e.g., lateral motion, static contact, enclosure action). In other words, participants in the modified PICTIVE more frequently used prototype widgets, which resulted in more interactive design environments. The results of gesture *type* analysis also support the results of gesture *purpose* analysis; in that, the most frequently observed gesture purpose in the modified PICTIVE was to refer to objects and understand objects (e.g., physical interactions with prototype widgets). These participants largely used their hands and arms in order to interact with prototype widgets.

4.3.3. Satisfaction

Nine closed-ended questions were incorporated to investigate the two design groups' satisfaction levels. The results revealed no significant difference between the two design groups, and both groups were highly satisfied. An additional open-ended question was used to allow participants to provide any further feedback they had. The two groups' comments showed somewhat different points of view on a given design method. Instead of judging a given design method, participants in the original PICTIVE considered their participation *per se* to be a contribution to the enhancement of assistive technology for others with visual impairment and appreciated the opportunity to work on the assistive technology design. Their appreciation probably somewhat contributed to the higher satisfaction scores. On the other hand, participants in the modified PICTIVE explicitly stated that they preferred manipulating haptic prototype widgets. They pointed out that the interaction with haptic prototype widgets positively influenced their design activities, such as improving their imagination and projection of 3D haptic virtual environments.

4.3.4. Time

The last variable for comparing the two design methods was the time it took a participant to perform a certain design task. It was postulated that the duration of design tasks would be different in the two design methods. Results confirmed that there was a significant difference, yet participants in the modified PICTIVE, on average, took 1.6 times longer to complete a design task compared to the original PICTIVE. However, this result does not mean that the modified PICTIVE was less efficient than the original PICTIVE. The duration for input and process tasks was not significantly different between the two design groups. The fact that participants in the modified PICTIVE spent more time was indeed caused by the output task. Participants in the modified PICTIVE had more design ideas to share, so they spent more time than did participants in the original PICTIVE. The primary reason for participants in the original PICTIVE method spending less time was that they simply agreed with a designer's idea or responded with no idea.

4.3.5. Overall discussion of the four variables

In sections 4.3.1 – 4.3.4 data analysis results were individually discussed. The following discussions are dedicated to exploring overall influences.

Many previous studies agreed on the notion that gesture is one of the prominent attributes of design activities. Yet, it has been unclear whether such a notion can be applied to those who have lost vision. Although Frame (2000) empirically observed gesture activities among participants with visual impairment, his study was not conducted on a design task but on a plain conversation session (e.g., introducing oneself, sharing personal experiences, and answering questions about age and grade). Based solely on Frame's study, it would be difficult to argue that people who are visually impaired also take advantage of gestural activity to communicate in a design task. On the other hand, the present research evidenced the use of gestures among individuals who are visually impaired in a design task setting. The present study contributes to correcting the misconception by demonstrating the use of gestures among people with visual impairment. In addition to the gesture types and purposes that were found in the literature review, the present study found additional gesture types and purposes, which were outlined in Table 26 and Table 27.

The present research found that participants' verbal and non-verbal communication (i.e., speech and gesture) facilitated the sending, receiving, and acknowledging of information, which is indeed consistent with McNeill's theoretical claim (2005) that thinking is deeply involved in the production of gestures and speech (see Figure 59). A lack of gesture is likely to reduce the amount of information that speakers can deliver and listeners can receive. If there is, however, an increase in the use of gesture, it means that people have the imagistic thinking facilitated. People with a higher frequency of gestures are regarded as being deeply interested and actively involved in ongoing conversations.

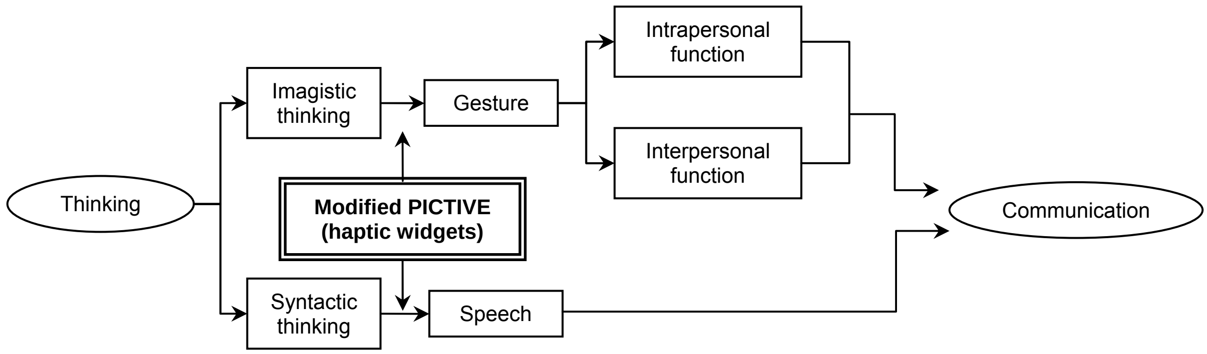


Figure 59. A schema of relations between thinking and communication influenced by the modified PICTIVE

The present research's empirical observation of a higher frequency of gestures in the modified PICTIVE implies that those participants were more deeply engaged in design processes and positively contributed to design activities compared to those in the original PICTIVE. The present research contends that incorporating haptic prototype widgets (or artifacts) in design processes facilitates participants' gestures and verbal communication (see Figure 59). In fact, participants in the modified PICTIVE more frequently showed such *gesture types* as contour following, enclosure, lateral motion, and relocation of an object, all of which were closely related to physical interactions with haptic prototype widgets. Furthermore, participants in the modified PICTIVE more frequently used their gestures for such *gesture purposes* as understanding an object and referring to an object, which are also related to haptic prototype widgets.

By using haptic prototype widgets, participants were able to obtain more rich information. Further, such an enhanced communication context facilitated the production of design idea and statements. Additionally, the enriched information about design contexts helped participants have a higher level of satisfaction with the design processes. In particular, participants in the modified PICTIVE pointed out that using different texture samples and small boxes was favorable to merely talking about designs in an abstract form. They reported that the wooden frame and haptic widgets were helpful to project the image of 3D virtual environments.

The aforementioned positive outcomes from the modified PICTIVE are also closely related to the result of participants in the modified PICTIVE spending more time on output processes. There was a trade-off between the positive outcomes (e.g., the amount of design ideas produced by participants) and the design completion time. Since participants in the modified PICTIVE had more design ideas, they needed more time to discuss them by showing more communicative gestures. They also enjoyed manipulating the haptic widgets and took more opportunities to use them to articulate their thoughts.

Previous research offers further theoretical perspectives as to how the haptic widgets influenced participants in the modified PICTIVE. The concept of shared mental models among group members has been viewed as a means to explain coordinated performance of a group (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Stout, Cannon-Bowers, Salas, & Milanovich, 1999). A shared mental model represents the extent to which a group of individuals share a similar cognitive representation of a certain situation or phenomenon (Langan-Fox, Wirth, Code, Langfield-Smith, & Wirth, 2001). The shared mental model theory predicts that a group with a greater shared mental model should more easily arrive at mutual understanding and common ground with regard to each member's informational requirements. This common understanding is likely to foster better communication among group members leading to improved performance (Stout et al., 1999).

Norman's concept of a mental model is consistent with the concept of the shared mental model theory. A mental model helps users shape their views of the world, of themselves, of their own capabilities, and of the tasks they are asked to do, or of something they are attempting to learn (Norman, 1983). A mental model allows users to describe, explain, and predict events in their environment. Norman's description of mental models encompasses four components: a target system, a conceptual model of the target system, a user's mental model of the target system, and a designer's conceptualization of that mental model. Ideally, the designer's conceptualization of a mental model and the user's own mental model are equivalent. An inaccurate mental model typically leads to errors. Therefore, the designer and a participant in the PICTIVE design method should arrive at a shared conception with regard to the target system design (i.e., haptic user interfaces in 3D virtual environments).

Given that the designer was already knowledgeable about the design tasks, the main concern in the present research was how to help a participant become well informed of the design contexts by considering the participant's vision loss. The present research made use of the sense of touch to give participants with visual impairment greater comprehension of their context. The tangible prototype widgets offered by the designer aimed to increase accessibility and help a participant obtain a better understanding about the haptic user interfaces in 3D virtual environments. Indeed, participants in the modified PICTIVE explicitly reported that they preferred manipulating haptic prototype widgets (e.g., small boxes with different textures and wood frames). Furthermore, they pointed out that using those widgets improved their imagination and projection of 3D haptic virtual environments. It can be interpreted that the haptic widgets helped the designer and a participant develop a similar mental model in the design task. Development of this shared mental model resulted in positive outcomes as measured by participants' statements related to design ideas, as well as by their gestures, time, and satisfaction.

None of the participants had been aware of the haptic technology before participating in the present study. Some had never heard the word *haptic*. However, they all understood it after the introduction sessions. In addition, it was found that participants had different levels of computer experience. For instance, one older participant used email and the Internet on a daily basis and often took advantage of assistive technology applications such as ZoomText. She had regularly taken a computer course provided by a local community non-profit organization for people with visual impairment. On the contrary, certain younger participants had a relatively lower level of computer experience and did not use the Internet on a daily basis. However, such varied computer experience does not imply that some participants were not qualified to participate in the present study. In fact, they all understood terms used in the present study such as drop-down menus, right-clicks, and shortcut keys.

The researcher attempted to behave the same way when working with both design groups so as not to introduce researcher bias, though it is conceivable that the researcher's behavior changed subconsciously.

In addition to the development of a more accessible participatory design method for users with visual impairment, the developed design process can also be useful to professionals with visual impairment and students with visual impairment in Human Factors and HCI domains. Some of the accessibility features of the modified PICTIVE (e.g., touch-based prototyping interactions) can be applicable to other participatory-design approaches as well. As a long-term contribution, the present study's results could motivate other researchers to investigate the applicability of other traditional design methods to nontraditional user interfaces for users with disabilities.

Experiences from the present study led to the development of a checklist containing a list of items required, aims to be accomplished, and points to consider when using the modified PICTIVE design method with a participant who is visually impaired. The following checklist should give designers and researchers insight into planning, preparing, and conducting the modified PICTIVE design method.

1. Planning
   Identifying participant characteristics
   - [Y/N] Referring to the World Health Organization (WHO) classifications of visual impairment with Snellen visual acuity values (WHO, 2008a)
   - [Y/N] Preparing a user profile (e.g., current age, age of onset of vision loss, duration of vision loss, Braille reader, and large print reader)

   Recruiting participants
   - [Y/N] Finding key contacts and constructing partnerships (e.g., organizations for specific disabilities, cross-disability organizations, mailing lists, services for students with disabilities in a college/university, local disability-related support groups, local/regional government rehabilitation or disability services departments, senior organizations/local senior centers, independent living organizations)
   - [Y/N] Participating in conferences with regard to people with visual impairment and assistive technology
   - [Y/N] Volunteering at events for people with disabilities
   - [Y/N] According to Virzi (1992), four or five participants are enough to find approximately 80% of usability problems. Any additional participants are less likely to contribute to revealing new information. Practitioners in an iterative design process are, for instance, expected to save time, resources, and budgets.

   Choosing the best location
   - [Y/N] Considering assistive technology needs
   - [Y/N] Taking into account transportation
   - [Y/N] Ensuring accessibility of the facility

   Scheduling the right amount of time/break time
   - [Y/N] Considering the health conditions, modality impairments, and energy level of participants
   - [Y/N] Taking into account time to set up for the design task
   - [Y/N] Planning time for a participant to become familiar with design tasks
2. Preparing for design activities
   - [Y/N] Video camera(s) and tapes
   - [Y/N] Everyday office materials (e.g., rubber band, glue, magnet, paper clip, adhesive tape, scissors, and thick paper)
   - [Y/N] Haptic prototype widgets (e.g., various grits of sandpapers, small-sized cardboard boxes for interface components, navigation buttons)
   - [Y/N] Simulated virtual environment (e.g., a cardboard box with a wooden frame)
   - [Y/N] Consent forms and other documents, written in clear and simple language, and prepared in alternative formats such as large print, Braille, electronic, and audio
3. Conducting design activities
   Setting up the room
   - [Y/N] Ensuring that the facility is accessible
   - [Y/N] Not moving anything without informing a participant

   Orienting a participant
   - [Y/N] Explaining unusual noises and activities (e.g., clicking camcorder buttons, opening/shutting doors)
   - [Y/N] Offering an elbow to lead a participant with visual impairment
   - [Y/N] Giving directions about where to be seated
   - [Y/N] Not interacting with a guide dog or service animal

[Y/N] Telling a participant where a place for the guide dog is located
Completing paperwork
[Y/N] Consent forms and other relevant paperwork
[Y/N] Indicating the place for signature if a participant cannot locate it
[Y/N] Vision acuity check (e.g., Snellen chart)
[Y/N] Completing design tasks
[Y/N] Providing compensation (and identifying the amount of compensation when giving it to a participant with visual impairment)

As discussed earlier, the gesture can be regarded as a factor that is differently influenced by the degree of vision loss (Frame, 2000). According to Blass's theoretical claim (Blass, Freedman, & Steingart, 1974), body movements (gestures) are closely associated with communication and can affect a listener. Thus, an interesting line of research would be to explore what effect a user group with total blindness has on the production of gestures and effectiveness of the modified PICTIVE. Another possible variable to consider would be the effect of a designer with visual impairment. For instance, do participants with visual impairment change the way they use gestures while interacting with a designer who is also visually impaired?

4.4. Data analysis (documentation of HUI user needs)

While conducting the comparative study of the two PICTIVE design methods, additional research efforts were devoted to the documentation of HUI user needs. Indeed, this analysis was not a primary purpose of Study 2, but it was intended to prepare a set of user needs to be used in Study 3. When designing the fundamental haptic user interfaces, participants' statements referred to their needs with regard to a future haptic system's user interfaces. Given the video that captured participants' statements, this research followed a systematic approach to document user needs, such a usability technique as an affinity diagram (Beyer et al., 1998) that was often used when developing a set of user interface design guidelines (Kim et al., 2008; Lee, Smith-Jackson, & Kim, 2008). According to the recommendation of Lee et al. (Lee et al., 2008), a research group was set up and consisted of three individuals who had experience in user interface design or user study. As a result, the group was composed of three graduate students who had experience with usability studies. For instance, the research group attempted to sort HUI user needs into specific groups and, subsequently, organized the set of user needs by iteratively reviewing them within each category, as well as relocating, eliminating, or merging them from their initial categories (See Figure 60). The categories were made more distinct by generating subcategories, if necessary. This process continued until all members of the usability research group reached mutual agreement.

Figure 60. Example of an affinity diagram

4.5. Results (documentation of HUI user needs)

Those user needs were documented under three categories: audition, touch, and vision. A full list of user needs in detail is available in Appendix D. The following sections present discussion of those user needs.

4.5.1. Audition

Participants with low vision viewed the sense of hearing as one means to facilitate their communication with a haptic device. They expected two types of feedback: speech and non-speech auditory feedback.

Speech

Participants wanted to be briefly informed of the whole structure of user interfaces before performing any activity. For instance, they expected a system to introduce the locations or the number of virtual haptic widgets line by line. Such a quick update on the overall structure can help users with visual impairment to build a mental image of user interfaces, which would contribute to the improvement of a user's space perception. Besides the overall system introduction, a detailed level of haptic user interfaces can also be introduced; for example, a human voice could describe main features (e.g., shape, size, or function) of haptic widgets when a user's virtual pointer touches them. In addition to understanding haptic widgets, movements in the 3D virtual environments could be facilitated as well. For instance, when a user seeks a certain haptic widget, verbal feedback could describe a route to a target (e.g., main controls).

<u>*Non-speech*</u>

In addition to speech auditory feedback, non-speech auditory feedback was also found to be preferred among participants. Non-speech sound can facilitate a quick update on interactions between a system and a user with visual impairment. For example, non-speech sound can be used in the following situation: a user pushes a virtual button to trigger an event, but he or she is unsure whether the virtual button is fully pushed down to function. To quickly and efficiently inform a user of the button's status, a system can produce a click sound once the button is pushed down. Additional clues could contribute to a user's understanding.

Furthermore, participants suggested that non-speech auditory feedback can also be implemented to help a user recognize, diagnose, and recover from errors. In real life, those with visual impairment typically understand a widget by touching and following its contour. By applying the typical approach of those with vision loss, the following design was suggested: when a user loses contact with a widget, a system should immediately generate such non-speech feedback as beep. In addition, participants wanted to have simple auditory interfaces (e.g., a small number of sound samples) so that they could reduce cognitive workload in memorizing the meanings of sound samples.

4.5.2. Touch

<u>*Accuracy*</u>

Participants recommended that a system should provide consistency in user interfaces through the whole system. For instance, a reference point should be available in virtual environments and should be placed at the same location through all sub-pages, thereby helping a user with visual impairment to have a more accurate perception of space. In addition, a user should be allowed to assign a certain point as a reference point based on a user's preference.

Automatic guidance by a system can help a user locate a certain object or place. The automatic guidance could be used when a user loses contact with a virtual widget while following its contour or gets lost while navigating in 3D virtual environments. Such automatic guidance could reduce a user's cognitive workload and help a user concentrate on his or her primary work.

Force bandwidth

When a user touches a virtual button, a series of force feedback (e.g., vibration) can be used as a confirmation message. A system should keep users informed about what is happening through appropriate feedback within a reasonable time.

Force magnitude

A detent force can serve as a clue for a user to distinguish a horizontal gap between buttons. When a user is in the process of locating and clicking two closely placed buttons, there is a possibility that he or she will fail to recognize the gap between buttons. As a result, two buttons are perhaps recognized as a single button. A magnetic force should be placed between two virtual buttons, which would help a user to feel strong detent force and recognize it as a gap while moving between two buttons.

Sensing acuteness

Various designs can be used to improve users' sensing acuteness in VE. For example, different textures can be assigned to virtual widgets that are closely located. Tactile clues can help a user reduce memory load. In particular, the edge of an object is favored as a place to assign texture because the edge is the first place a user with visual impairment is likely to touch to understand an object's characteristics in the real world. Matching between a system and the real world would increase a user's sensing acuteness.

In addition to varying texture, shape is also one of the critical HUI design issues for enhancing acuteness. For example, participants preferred a convex (i.e., bulging outward) button to a concave (i.e., inward-curving) button. They thought that a convex button is more distinctive and increases the likelihood of being detected by touch. It is important to prevent a problem from occurring in the first place. A designer should eliminate any error-prone conditions. Hence, using a convex button type is encouraged in VE for a user with vision loss.

Another concern addressed how disabled buttons or menus should be designed for a user with visual impairment. Disabled buttons or menus can still be used as reference points for a user with visual impairment. If buttons or menus disappear, a user with visual impairment might be confused in terms of space perception. Those buttons or menus should be somehow detectable. When a button is pushed down, the button might be designed to return immediately to the original height, but also different textures can be assigned to the on-off button. In graphical user interfaces, activating a button makes its associated content visible, and the button itself usually becomes highlighted with different colors to distinguish it from other inactive ones. In haptic user interfaces, different textures could be used instead of different colors.

Workspace size

A 3D virtual space should have a boundary that is detectable by touch. In a 3D-based virtual environment, users with visual impairment are likely to get lost and wander away from a working area. In general, graphic user interfaces have a container, that is, a “window.” Sighted users are able to see their mouse pointer’s location and movement and understand whether they are inside or outside of a window. In haptic user interfaces, the working space can be represented by a virtual boundary. When a user tries to reach over the boundary, the boundary is made known by locking a user’s virtual pointer. In order to enhance a users’ space perception, a system could be designed to provide a user with an opportunity to perceive the whole space size. For instance, a system could guide a user to touch, follow, and feel the boundary once a user enters a working space. Such a design is consistent with the visually impaired user group’s behavior in real life; that is, those with visual impairment typically tend to scan a working area by moving hands or a cane to perceive its size.

Velocity

A user should be allowed to adjust the 3D virtual pointer speed. It is likely that users with low vision would have difficulty following a fast moving 3D virtual pointer on screen. Being able to adjust the virtual pointer speed is necessary for such users. If a user wants to play a fast-paced application, a faster pointer speed is probably desirable. However, sometimes a user also wants to play with a delicate move.

4.5.3. Vision

Users with low vision are still able to rely on their sight to interact with a system. The design of graphical user interfaces is still important for those users. Color enhancements could help to improve the clarity of contents in the 3D virtual space. For instance, color should be changeable to various options, such as black and white, yellow on black, and inverted brightness. The clarity of contents generally contributes to a user's easier viewing and reduces eyestrain.

In addition to the enhanced color contrast, an icon could also facilitate users' interaction with a system. A three-dimensional coordinate (with origin O and axis lines X, Y, and Z), for instance, can help a user to locate himself or herself in a 3D virtual space.

All widgets in the 3D virtual space should not be arranged on the same sagittal plane (i.e., parallel to the midline of the body). In contrast with 2D widgets, 3D widgets that are arranged on the same line or plane are more likely to appear to be a single object (see Figure 61). Even better than a good error message is a design that prevents a problem from occurring in the first place. A designer should be careful in handling the arrangement of widgets in a 3D VE.

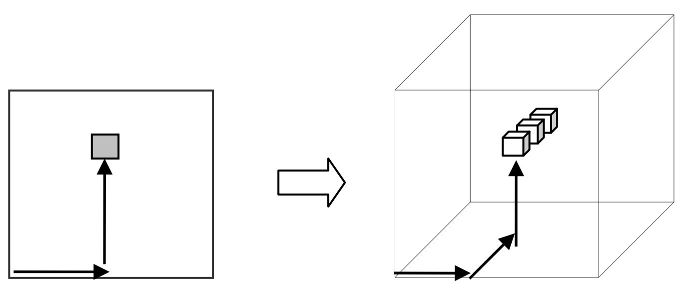


Figure 61. Identical widgets placed on the same sagittal plane

4.6. Discussion (documentation of HUI user needs)

The primary aim was to document the needs of users with visual impairment with regard to haptic user interfaces (HUIs). In particular, the present research was set up to explore the following key design interactions: navigating, finding objects, getting an overview, understanding an object, and discriminating between objects. Given design situations related to those user interactions, participants produced HUI needs. The needs were then segmented into three categories: audition, touch, and vision. Additionally, the categories were made more distinct by generating sub-categories.

Participants with visual impairment in the present study viewed the sense of hearing as one means to facilitate their communication with a haptic device. For instance, they wanted to be briefly informed of the whole structure or detailed levels of haptic user interfaces through auditory feedback before beginning any activity. Their needs were indeed consistent with the study results of Yu, Ramroll, and Brewster (2001), which recommended that visual information represented by haptic technology be supported by speech auditory feedback. Their empirical study showed that haptic graphs could be useful for users with visual impairment to understand the overall shape and layout; however, the results revealed that users with visual impairment failed to understand exact values of the points on haptic graphs. Yu et al. contended that an additional sensory modality, such as speech, is required to speak out the value when users press a key on the keyboard or a button on an input device (e.g., stylus) of the haptic technology application.

In addition to speech auditory feedback, participants in this research also expressed a preference for non-speech auditory feedback. They indicated that non-speech sounds also provide a quick update on interactions between the system and a user with visual impairment. The idea of using non-speech audio was also considered in a set of design guidelines provided by Brown et al. (2003). Those researchers studied the impact of presenting graphs and tables to users with visual impairment through non-speech audio; they found that mapping values to musical notes was a useful way to represent complex data (e.g., representing higher y-values with higher pitches). Furthermore, Brown's study addressed the relations between the memory capacity of users with visual impairment and speech output. According to their study, when the audio feedback was played fast, users with visual impairment had difficulty in interpreting it; on the other hand, when the audio was played too slowly, they had difficulty remembering the shape of a graph. This empirical study also produced a detailed design guideline, namely, that there should be a delay of 50 to 70 milliseconds between tones in a series.

Participants in the present study suggested that haptic user interfaces include a reference point in virtual environments. They believed that such an aid would increase the accuracy of their performance. Indeed, Colwell et al. (1998) observed that the performances of users with visual impairment decreased without a reference point in haptic virtual reality space. More specifically, various virtual objects with different features (e.g., sizes and angles of rotation) were presented to users with visual impairment, and those users were asked to estimate a given object's features. However, the results showed that most did not accomplish the task successfully. In addition, those users often tended to get lost in virtual space while searching for an object. Colwell et al. stated that the poor performance was due to the lack of a reference point in virtual space.

Participants also discussed how force feedback should be implemented and designed. For instance, they like to receive a confirmation message through force feedback (e.g., vibration), the aim of which is to inform a user that a certain region or object (e.g., a button) has been touched or fully pushed down. Such a confirmation cue via the touch modality has been recognized as an essential aspect of haptic technology designs (Cruz-Hernandez, Grant, & Ramstein, 2008). In fact, several researchers have implemented virtual haptic pushbuttons with such features as a sudden popping and a hard stop as means of confirming an intended input (e.g., being fully pushed down) (Miller & Zeleznik, 1999).

In addition, participants in the present study suggested that force feedback could be used to guide users in virtual space. For example, a magnetic force could be placed between two virtual buttons so that a user would feel strong detent force when moving across the two buttons. Such a user interface of detent force (also referred to as gravity wells) has been widely applied to the design of haptic user interfaces for users with motion impairment (Hwang, Keates, & Clarkson, 2003). This type of force feedback has been found to contribute to improvement of targeting time and reduction of errors (Hasser, Goldenberg, Martin, & Rosenberg, 1998; Oakley, McGee, Brewster, & Gray, 2000). Using the gravity well is also believed to enhance the performance of users with visual impairment (Christian, 2000). In fact, the user interface of the gravity well has been used in haptic-embedded educational software for younger students with visual impairment (Yamaguchi et al., 2009).

Participants in this research shared the design recommendation that a sense of touch could facilitate their experience and interaction with virtual environments. For example, they believed that assigning different textures to the edge of an object could improve a user's sensing acuteness and prevent them from getting lost in virtual space. In fact, Colwell et al. (1998) observed that users with visual impairment often experienced getting lost in virtual environments, a condition described as being "lost in haptic space." More specifically, those users moved their probe along a virtual cube and, when reaching the edge of it, slipped off, thus losing track of where they were and wandering around in virtual space. Colwell' study merely recommended giving users sufficient practice time to become familiar with the navigation activity, while participants in the present study suggested a more detailed design idea; that is, assigning textures to the edge of an object.

In addition to texture, shape was also viewed as a helpful haptic user interface in enhancing acuteness. Participants preferred convex over concave buttons. Fritz, Way, and Barner (1996), who proposed design techniques for effectively representing scientific data through haptic technology, introduced concave and convex types of interfaces, although no comparative study of the two types was conducted. Many researchers have agreed that users' accurate perception of virtual objects is a critical design issue and that more attention should be paid to sensing acuteness in the design of virtual objects. For instance, users typically perceive virtual objects to be bigger from the inside but smaller from the outside, in what is called a tardis effect (Carter & Fourney, 2005; Colwell, Petrie, Kornbrot, Hardwick, & Furner, 1998). There is no need to concern about the tardis effect in designing graphical user interfaces but haptic user interfaces. A haptic user interface designer should bear in mind that certain design guidelines for graphical user interfaces cannot be applied to haptic user interfaces and that a new design guideline or concept may be needed.

Another concern was how to handle a disabled button. Participants shared the design idea that a disabled button should remain in virtual space and be detectable in some way, such as through the assignment of a different texture. A recent study (Sjostrom, 2002) also took into consideration the design of disabled buttons in haptic user interfaces and offered a similar suggestion, stating that disabled buttons should not be removed but only made nonfunctional because they can serve as a reference point for users with visual impairment.

The concept of haptic boundary was also discussed in participatory design sessions in the present study. The haptic boundary helps users feel the working area (e.g., a window in graphical user interfaces) and prevent them from getting lost in virtual space. When a user tries to reach over the boundary, the user's virtual pointer locks. Subramanian et al. (2005) provided a more detailed design guideline, stating that the forces should be strong enough to keep a user from crossing the boundary, but not so strong to limit the user's movement. Another study (Brown, Brewster, & Ramloll, 2003) suggests the use of auditory rather than force feedback; for instance, users could hear a non-speech sound when they reach the boundary of a table or a graph. Their empirical study showed that users were likely to become confused without the auditory boundary.

Users with low vision are still able to rely on their sight to interact with a system so that the design of graphical user interfaces is still important for those users. In general, the primary concerns commonly faced by users with low vision include color perception deficits, impaired contrast sensitivity, and loss of depth perception (Gulliksen, Harker, & Steger, 2001), which should carefully be considered in designing graphical user interfaces of haptic technology. For example, users with low vision encounter difficulties in locating or tracking pointers, cursors, targets, and hot spots; as a result, assistive technology applications frequently use oversized views, large fonts, high contrast, and magnification to enlarge certain portions of the display (Gill, 2001; Stephanidis, 2001). Those concepts could also be applied to designing a haptic technology application for users with low vision. In fact, participants with low vision in this research also produced similar design ideas, such as a color enhancement and a viewable display placed at the user's eye level.

Overall, participants recommended that haptic user interfaces be developed based on multimodal interactions. In other words, users should be able to interact with a system through visual, haptic, and auditory channels. While many studies have provided ergonomic insight into the design of haptic user interfaces, they generally focused on a unimodal interaction (Brooks, Ouh-Young, Batter, & Kilpatrick, 1990; Kuber, 2006; Kuber et al., 2007; Liffick, 2003; Sjostrom, 2001b). In addition, those prior studies merely focused on sighted users and users with total blindness not users with low vision. Furthermore, those studies produced complex dimensions and properties of the HUI designs so that designers are likely to encounter difficulty in using those resources in a practical situation. In fact, there were researchers who understood the problem and made an effort to systematically organize the existing design guidelines of haptic user interfaces through the GOTHI-05 workshop (Guidelines On Tactile and Haptic Interactions), Saskatchewan, Canada, October 2005.

Researchers at the workshop worked together to develop a collection of ergonomic guidelines and a framework for tactile-haptic interactions. Afterward, an inaugural meeting of the ISO TC159/SC4/WG9 committee further elaborated those researchers' initial works, used as the basis for structuring its new series of ISO standards on tactile and haptic interactions (e.g., ISO 9241-910). The GOTHI framework includes five main categories: (a) tactile/haptic inputs, outputs, and/or combinations, (b) attributes of tactile/haptic encoding of information, (c) content-specific encoding, (d) interaction tasks, and (e) interaction techniques. The design issues that were considered by the present research also fit into the GOTHI framework, especially the fourth category (i.e., interaction tasks). As mentioned earlier, the HUI user needs in the present research were developed based on fundamental haptic interactions including navigation, finding objects/getting overview, understanding objects, and discriminating among objects, which were indeed all covered by subcategories of the fourth category, interaction tasks, in the GOTHI framework.

However, the GOTHI framework was not intended for users with visual impairment. In that regard, the HUI design categories in the present research can provide insight into HUI designs for users with visual impairment especially low vision. The outcomes of the present study can help HUI designers ensure that their analyses and designs appropriately consider the possibilities and constraints of haptic technology and, accordingly, reflect the design of haptic interactions for users with visual impairment. In contrast with the GOTHI framework, the HUI designs in the present research support multimodal interactions through visual, auditory, and haptic modalities. Designers should keep in mind that users with residual vision rely on not only touch/hearing but also seeing. The present research supports a more comprehensive model of HUI designs for users with visual impairment.

All participants had a similar amount of prior experience and knowledge with regard to haptic technology applications. Although the present research invited participants from various locations, they were all living within Virginia. Thus, it might be difficult to argue that the outcomes of the present research reflect needs of the whole population with low vision; however, at least the outcomes would give designers some ideas as to how the HUI interactions can be used with other sensory modalities for heterogeneous user groups (e.g., younger and older users with low vision). In addition, the present research outcomes might be challenged with respect to the sample size. However, it has been accepted in HCI/Human Factors domains that a usability study with a large number of participants does not generate significantly more information than one with fewer participants (Spool et al., 2001). Well-known researchers, Nielsen and Virzi, pointed out that four or five participants are enough to identify approximately 80% of usability issues. Many researchers indeed employ four or five participants for their studies. This logic can also be applied to participants with visual impairment (Jones et al., 2005).

As stated earlier, the present research did not aim to explore comprehensive user needs but rather to prepare a list of user needs to investigate individual differences in Study 3. Therefore, the prepared list of user needs might not be comprehensive. However, a large set of user needs is not necessarily more meaningful, superior to a small number of user needs. Both types are considered useful in design (Nesbitt, 2005). For instance, a very detailed and comprehensive list of user needs can be functional when designers attempt to make very small and precise changes to user interface designs. On the other hand, a small number of general design principles can contribute to shaping of the overall direction or philosophy of a design. Both types are necessary to assist designers in developing user interfaces at various phases of the design process.

In fact, many prior studies on haptic technology paid more attention to the technical enhancement and demonstration of its benefits than to a user study. Despite such a small number of user needs, the present study's outcomes can contribute to the enrichment of a user study. In particular, Human Factors and HCI designers can learn how to implement haptic interactions for users with visual impairment. As a long-term benefit, such a careful design consideration would eventually help to resolve the following questions: What types of information can be effective in harmony with users' haptic modality? Do users with visual impairment perceive haptic feedback differently? How should haptic feedback be implemented and presented along with auditory and visual feedback?

In addition, the outcomes (i.e., HUI user needs and categories) support a heuristic analysis method for evaluating and designing a 2D/3D-based haptic device. The heuristic analysis is typically accomplished through a series of steps, including (step 1) defining a set of primary tasks or scenarios for a target device, (step 2) defining a heuristic list, (step 3) familiarizing with a target device, (step 4) performing each task identified in step 1 and evaluating it by using the heuristic list in step 2, and (step 5) proposing remedies. In particular, the present research can contribute to the first and second steps. More specifically, this research offered a set of users' primary tasks with haptic technology systems, such as navigating in a virtual environment, finding objects and getting an overview, understanding features of an object, and discriminating between objects. In addition, the list of user needs can be used as a heuristic list in the heuristic analysis process. The list of user needs will help designers determine which usability aspects should be carefully evaluated. Finally, the outcomes in Study 2 were used in Study 3 to investigate the vision- and age-related individual differences associated with haptic user interface designs.

CHAPTER 5. STUDY 3: HUIs User Needs

5.1. Method

The objective of Study 3 was not to collect user needs, but rather to explore the degree to which participants shared common user needs in HUIs.

5.1.1. Experimental design

Study 3 consisted of two parts: an age-related individual-difference study and a vision-related individual-difference study. Independent variables included age (younger and older) and vision (low vision and intact vision). The dependent variable was participants' agreement on the list of haptic user interface needs (see Table 30). Two independent samples (i.e., between-subjects design) were employed in Study 3.

Table 30. Independent and dependent variables

	Age-related individual-difference study	Vision-related individual-difference study
Independent variable	Age (younger and older)	Vision (low vision and intact vision)
Dependent variable	Participants' agreement on the list of haptic user interface needs	Participants' agreement on the list of haptic user interface needs

5.1.2. Participants

The sample size was statistically estimated using the formula below (Ott et al., 2001; Quinn et al., 2002).

$$n \geq \frac{\sigma^2}{\Delta^2}\left(z_{\alpha/2}\right)^2$$

,where σ is the standard deviation of users' rating scores, and Δ is the difference between μ_0 and μ_1. These values are typically determined based on the results of pilot tests or previously published studies with similar equipment and participants (Quinn et al., 2002). The present study used a previous study of Yu, Ramloll, and Brewster (2001) as its referent. Yu conducted research with a haptic technology application (i.e., PHANToM device, SensAble Technologies, Inc.) and participants with visual impairment.

More specifically, sighted participants and those with visual impairment were asked to complete a questionnaire (i.e., closed-ended rating scale questions) to report what they liked most and least about haptic interfaces that were designed to make graphs accessible through haptic and audio media. Their research results were used to obtain the values needed for sample size estimation. The standard deviation was thus considered to be 2.59. Additionally, the difference between μ_0 and μ_1 was assumed to be 2.40. Given α = .05, 10 participants per group were engaged in this research, which is deemed to be sufficient to reliably detect a statistical difference in users' preferences with a system, with a risk for a Type I error of .05 and a Type II error of < .03, with a power greater than .70.

The criteria used in Study 1 were used again to distinguish participants by age and vision. After screening, 10 younger individuals (less than 30 years of age) with low vision and 10 older individuals (65 years or older) with low vision were invited to the age-related individual-difference study. For the vision-related individual-difference study, 10 individuals with low vision (less than 30 years of age) and 10 sighted individuals (less than 30 years of age) were invited (see Table 31).

Table 31. Participant classifications

	Age-related individual-difference study			Vision-related individual-difference study		
Participants	▪ Age (younger and older) o 10 younger participants (less than 30 years of age) with low vision o 10 older participants (65 years or over) with low vision			▪ Vision (low vision and intact vision) o 10 participants with low vision (less than 30 years of age) o 10 participants with intact vision (less than 30 years of age)		
		Younger	Older		Low vision	Intact vision
	Mean age (SD)	20.70 (5.21)	81.90 (6.87)	Mean age (*SD*)	20.70 (5.21)	21.70 (3.13)
	Mean age of onset of visual impairment (SD)	5.30 (8.98)	60.30 (17.42)	Mean age of onset of visual impairment	5.30 (8.98)	N/A
	Mean duration of visual impairment (SD)	15.40 (8.18)	21.60 (16.37)	Mean duration of visual impairment	15.40 (8.18)	N/A
	Mean visual acuity in decimal notation (SD)	0.13 (0.11)	0.18 (0.11)	Mean visual acuity in decimal notation (SD)	0.13 (0.11)	0.66 (0.30)

5.1.3. Materials and equipment

The user needs were extracted from Study 2 (see Figure 62). The extracted user needs were used to examine the degree to which participants shared a common preference for haptic user interface designs.

Each statement of the user needs was followed by a five-point Likert scale. It was assumed that the distance between each anchor was the same. The questionnaire format was consistent with the design guidelines developed by Kaczmirek and Wolff (2007). Participants were allowed to choose one of several questionnaire formats, including Braille and large print. The questionnaire was similar to that illustrated in Table 32.

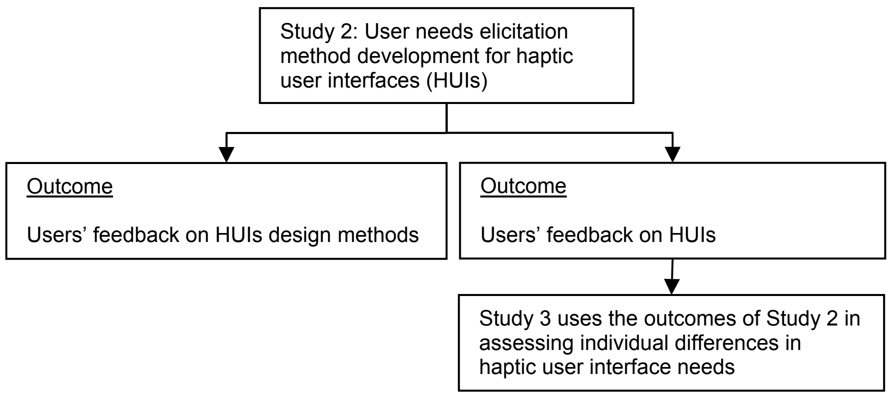
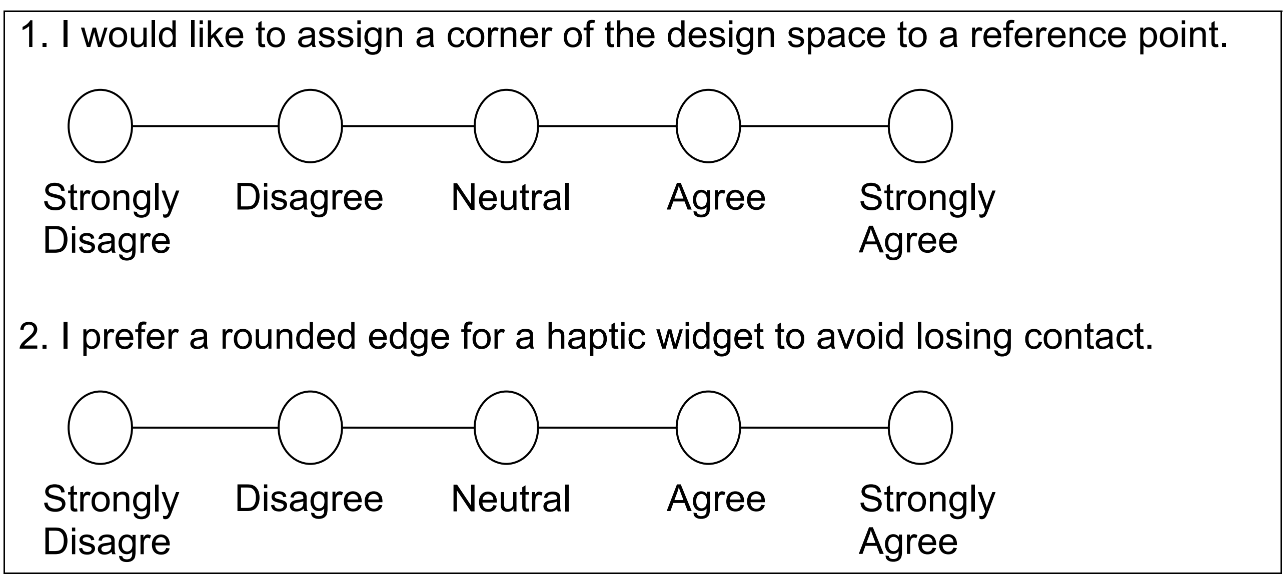


Figure 62. Questionnaire development

Table 32. The sample items



A participant's vision acuity was measured with a Snellen chart. A participant was instructed to stand behind a line 20 feet from a wall-mounted Snellen vision chart. The participant covered one eye with an eye spoon and read aloud from the top line of letters (i.e., the largest letter) to the smallest line of letters that a participant can see. If a participant used the eye spoon, he or she was instructed not to apply pressure to the occluded eye because pressure can cause blurred vision and thus skew the results (Haupt, 2008). This procedure was repeated for the other eye. The vision of each eye was recorded separately. The participant's vision acuity was represented by the acuity in the better eye with the best possible correction, according to the WHO classification of visual impairment.

5.1.4. Procedure

The procedure included IRB, familiarity procedure, vision acuity check, HUI exploration, and an evaluation phase (see Figure 63).

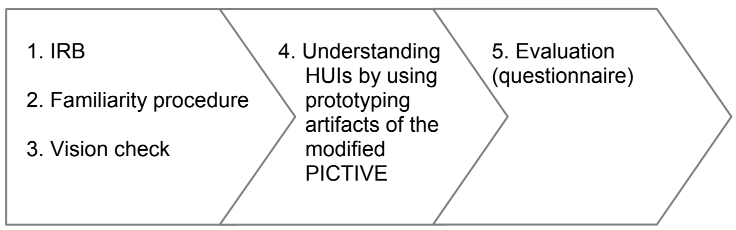


Figure 63. Evaluation procedure for HUIs

A participant was asked to review the informed consent form and sign it. The informed consent form was offered in various formats, including Braille and large font paper. A participant was given the informed consent form in his or her preferred format. The researcher indicated the location for the signature, if needed. A participant kept one copy of the informed consent forms, but the other copy was kept by the researcher.

A participant was guided in becoming familiar with the experimental equipment, procedures, and environments where the experiments were conducted, such as the arrangement of chairs, desks, doors, and safety-related gadgets, if available. After the orientation procedure, the researcher did not move anything in the room without informing the participant. It was ensured that the location for the experiment was safe from any potential barriers. In addition, there were other considerations the researcher kept in mind: (a) explaining unusual noises and activities (e.g., clicking camcorder buttons, opening/shutting doors), (b) offering an elbow to lead the participant, (c) giving directions about where to be seated, (d) not interacting with a guide dog or service animal, and (e) telling the participant where there was a room for the guide dog. A short amount of time was assigned to a warm-up period in which a participant and the researcher shared personal information.

A Snellen vision chart was used to measure participants' vision acuity to ensure they fell into one of two categories: category 1 (moderate visual impairment) or category 2 (severe visual impairment).

In this phase, a participant was given a set of HUI user needs (also referred to as HUI design ideas). As already discussed in the literature review, the concept of haptic user interfaces was relatively new and might be difficult for participants to imagine. To reduce a participant's burden and facilitate the understanding of haptic user interfaces, the touch-based, low-fidelity prototyping artifacts and design situations that were used in Study 2 were used once again.

A participant was instructed to rate each HUI design idea by indicating how much he or she agreed with it. A participant completed the questionnaire individually (see Table 32). While completing the questionnaire, a participant was permitted to manipulate the prototype artifacts. A participant was compensated at a rate of $10 per hour. Sessions lasted approximately 60 to 90 minutes.

5.1.5. Data analysis

The Shapiro-Wilk tests were performed to check the normality of the data. Based on the results of the normality tests, participants' responses (i.e., agreement scores) were analyzed using an independent-samples *t*-test (for normal data) or a Mann-Whitney test (for non-normal data). More specifically, a statistical analysis was performed on a dependent variable with $\alpha \leq .05$ to test whether there was a statistically significant difference among groups of participants classified by age and vision. The independent variables were age (for the age-related individual-difference study) and vision (for the vision-related individual-difference study). The dependent variable was a set of agreement scores. The statistical analysis was conducted under the assumption of homogeneity of variance. The statistical analysis was conducted with SAS™ software version 8.2. Study 3 sought to answer the following research questions: To what extent do users with different visual impairment share a common preference for haptic user interface design? To what extent do younger and older users with low vision share a common preference for haptic user interface design? In particular, the following alternative hypotheses were considered:

- o Haptic user interface needs will differ for the two age groups.
- o Haptic user interface needs will differ for the two vision groups.

5.2. Results

5.2.1. Age-related individual difference study results

Research Question: To what extent do younger and older users with low vision share a common preference for haptic user interface designs?

H_a: Haptic user interface needs will differ for the two age groups.

This section discusses the statistical analysis results, with emphasis on Cronbach's alpha reliability, overall agreement, individual agreement, and mean agreement.

This research calculated Cronbach's alpha as the measure of internal consistency reliability. Both age groups were given 49 items (i.e., 49 HUI user needs), which they rated on a 1-to-5 response scale (i.e., 1 = *Strongly disagree*, 2 = *Disagree*, 3 = *Neutral*, 4 = *Agree*, 5 = *Strongly agree*). Statistical analysis results showed that Cronbach's alpha was .88 for older participants' responses and .67 for younger participants' responses. However, the younger group's alpha value increased to .81 when items 7, 16, 17, 41, 45 were excluded from the statistical analysis. According to Nunnally's study (1978), a Cronbach's alpha reliability coefficient above .70 can be viewed as acceptable. Therefore, this age-related individual-difference study attempted to keep the alpha value of .81. In other words, items 7, 16, 17, 41, 45 were excluded from the list of HUI user needs for the younger group. Additionally, items 7, 16, 17, 41, 45 were excluded from the list of HUI user needs for the older group because the two age groups were supposed to be compared under the same conditions. After items 7, 16, 17, 41, 45 were removed, the Cronbach's alpha of the older group's responses was .86.

Overall Agreement (summated rating): As shown in Figure 64, cumulative scores represented each participant's overall agreement with the ratings that he or she assigned to the list of HUI user needs. The cumulative scores of younger participants with low vision were compared with those of older participants with low vision.

	Younger participants with low vision			Older participants with low vision		
	Participant #1	Participant #2	...	Participant #1	Participant #2	...
Haptic user interface need #1						
Haptic user interface need #2						
:						
sum	x	x	x	x	x	x

Figure 64. A summated rating of participants' agreements on the haptic user interface needs in the age study

The Shapiro-Wilk tests indicated that the data were normal (younger, $W = .87$, $p = .10$; older, $W = .91$, $p = .30$). Therefore, the two age groups' scores were analyzed using an independent-samples *t*-test. This analysis revealed no statistically significant difference between the two age groups, $t(18) = -.73$, $p = .48$.

Individual Agreement (item rating): Individual scores represented each participant's agreement with the rating that he or she assigned to each item of user needs. The set of scores of the younger participants with low vision were compared with that of the older participants with low vision across all items (see Figure 65).

	Younger participants with low vision			Older participants with low vision		
	Participant #1	Participant #2	…	Participant #1	Participant #2	…
Haptic user interface need #1	xx	xx	xx	xx	xx	xx
Haptic user interface need #2						
:						
sum						

Figure 65. An item rating of participants' agreements on individual haptic user interface need in the age study

The Shapiro-Wilk tests were performed to check the normality of the data. Based on the results of the normality tests, individual agreement scores were analyzed using an independent-samples *t*-test (for normal data) and a Mann-Whitney test (for non-normal data). This analysis revealed statistically significant differences between the two age groups in terms of the following user needs:

- After hitting a virtual button, a user should receive verbal feedback about the button's function, such as Undo, Help, and Find; younger (*Mdn* = 5.00), older (*Mdn* = 4.00), $U = 22$, $p < .05$.

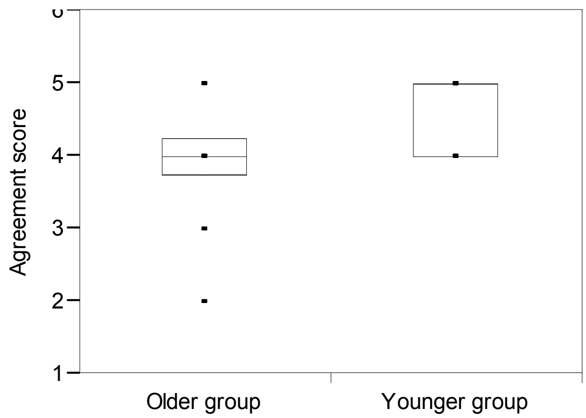


Figure 66. Agreement scores between the two age groups (*p* < .05)

- A user should be allowed to assign a certain point as a reference point based on the user's preference; younger (*Mdn* = 4.50), older (*Mdn* = 4.00), $U = 18$, $p < .05$.

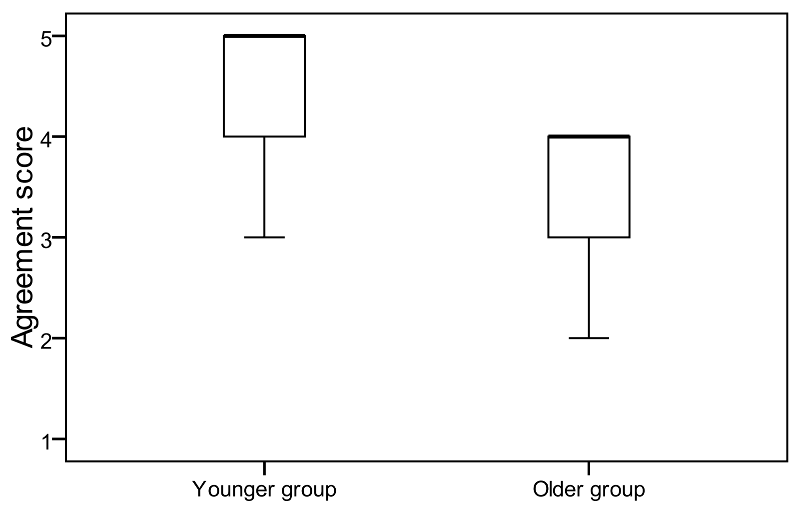


Figure 67. Agreement scores between the two age groups (*p* < .05)

- The color of user interfaces should allow a user to change colors, for example, black and white, yellow on black, and inverted brightness; younger (*Mdn* = 4.50), older (*Mdn* = 3.50), $U = 23$, $p < .05$.

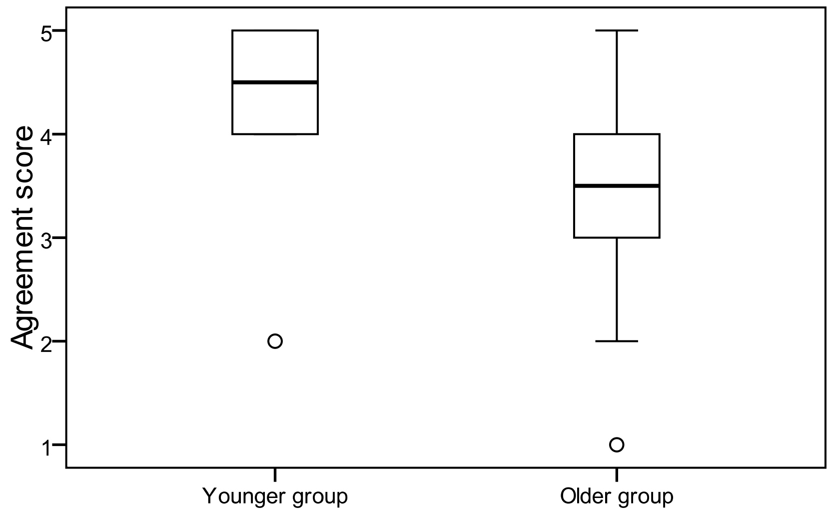


Figure 68. Agreement scores between the two age groups ($p < .05$)

With regard to the three user needs above, younger participants showed higher agreement scores compared to their older counterparts; however, both age groups' agreement scores were still above 3.50 (i.e., between *Neutral* and *Agree*), indicating that both age groups were in favor of the three user needs.

Mean Agreement: The previous sections discussed how much the two age groups agreed with regard to HUI user needs by comparing their overall and individual agreement scores. This section discusses the aim of screening out HUI user needs with lower agreement scores (i.e., below the score of 3 – *Disagree* and *Strongly disagree*) so that the present research can deliver a fine set of HUI user needs. Each statement of HUI user needs was labeled with numerical values from 1 to 49 to facilitate the data analysis (see Table 33). The detailed HUI user needs with labels can be found in Appendix D.

Table 33. HUIs user needs with the mean agreement score below 3

HUI user needs	Younger group's mean agreement	Older group's mean agreement
# 35: A virtual spherical widget should not be used.	2.40 [a]	2.90 [a]
# 43: Virtual widgets should not all be arranged on the same sagittal plane (parallel to the midline of body).	2.80 [a]	3.70

[a]*Mean agreement score below 3 refers to 'Strongly disagree' and 'Disagree'*

The results showed that younger participants assigned lower agreement scores to the two HUI user needs (i.e., # 35 and # 43), while older participants had one HUI user need with a lower agreement score (i.e., # 43). The two age groups' agreement scores showed no significant difference (for # 35, U = 34, p = .25; for # 43, U = 28, p = .11).

5.2.2. Vision-related individual-difference study results

Research Question: To what extent do users with different vision levels (i.e., low vision and intact vision) share a common preference for haptic user interface designs?

H_a: Haptic user interface needs will differ for the two vision groups.

This section addresses statistical analysis results for the vision-related individual-difference study, with emphasis on Cronbach's alpha reliability, overall agreement, individual agreement, and mean agreement.

This research calculated Cronbach's alpha as the measure of internal consistency reliability. Both vision groups were given 54 items (i.e., 54 HUI user needs), which they rated on a 1-to-5 response scale (i.e., 1 = *Strongly disagree*, 2 = *Disagree*, 3 = *Neutral*, 4 = *Agree*, 5 = *Strongly agree*). Statistical analysis results showed that Cronbach's alpha was .81 for sighted participants' responses and .59 for responses of participants with low vision. However, the low vision group's alpha value increased to .72 when items 39, 42, and 51 were excluded from the statistical analysis (see Appendix D for the full list with item numbers). According to Nunnally's study (1978), a Cronbach's alpha reliability coefficient above .7 can be viewed as acceptable. Therefore, this vision-related individual-difference study attempted to keep the alpha value of .72. In other words, items 39, 42, and 51 were excluded from the list of HUI user needs for the low vision group. Additionally, items 39, 42, and 51 were excluded from the list of HUI user needs for the sighted group because the two vision groups were supposed to be compared under the same conditions. After items 39, 42, and 51 were removed, Cronbach's alpha for the sighted group's responses was still .79.

Overall Agreement (summated rating): As previously shown in Figure 64, cumulative scores represented each participant's overall agreement with the ratings that he or she assigned to the list of HUI user needs. The cumulative scores of sighted participants were compared with those of participants who have low vision.

The Shapiro-Wilk tests indicated that the data were normal (low vision group, $W = .92$, $p = .37$; sighted group, $W = .94$, $p = .55$). Therefore, the two vision groups' scores were analyzed using an independent-samples *t*-test. This analysis revealed no statistically significant difference between the two vision groups, $t(18) = 1.38$; $p = .19$.

Individual Agreement (item rating): The individual score represented each participant's agreement with the rating that he or she assigned to each item of user needs as previously shown in Figure 65. The set of scores of participants with low vision were compared to that of sighted participants across all items.

The Shapiro-Wilk tests were performed to check the normality of the data. Based on the results of the normality tests, individual agreement scores were analyzed using an independent-samples *t*-test (for normal data) and a Mann-Whitney test (for non-normal data). This analysis revealed statistically significant differences between the two vision groups for the following two user needs. With regard to the two user needs below, the low vision group showed higher agreement scores compared to the sighted group. In particular, the agreement score of sighted participants on the first user need was slightly lower than 3, indicating that sighted participants did not prefer a raised line on the edge of a virtual widget in contrast with participants with low vision.

- A user prefers a raised line on the edge of a virtual widget rather than a grooved line; low vision group (M = 3.90, SD = 0.99), sighted group (M = 2.90, SD = 0.99), $t(18) = -2.25$; $p < .05$.

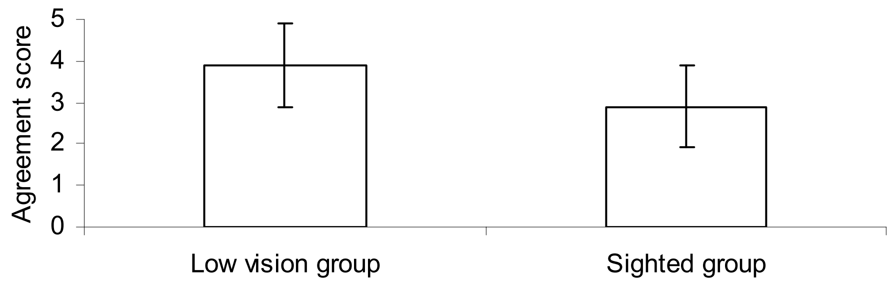


Figure 69. Agreement scores between the two vision groups (*p* < .05)

- Virtual widgets should be arranged on a horizontal line instead of a vertical or curvy line; low vision group (Mdn = 4.00), sighted group (Mdn = 3.00), U = 18.50, $p < .05$.

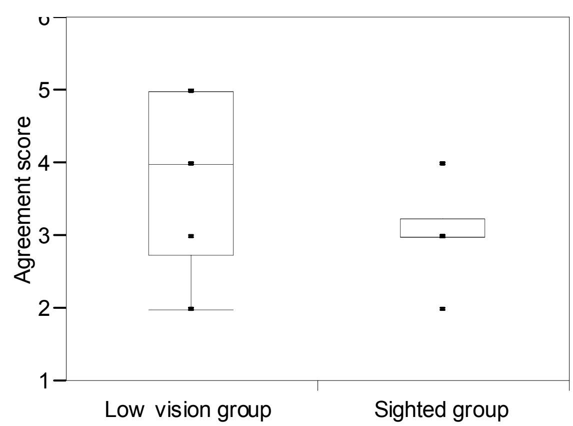


Figure 70. Agreement scores between the two vision groups (*p* < .05)

Mean Agreement: In this section, the primary aim was to screen out HUI user needs with lower agreement scores (i.e., below the score of 3, which includes *Disagree* and *Strongly disagree*) so that the present research can deliver a fine set of HUI user needs. Each HUI user need was labeled with numerical values from 1 to 54 to facilitate the data analysis (see Table 34). The detailed HUI user needs with labels can be found in Appendix D.

A low vision group showed a lower agreement score on one HUI user need (i.e., item 9), while a sighted group indicated lower agreement scores on four HUI user needs (i.e., items 9, 11, 17, and 30).

Table 34. Mean agreements of two vision groups (below the score 3)

HUI user needs	Mean Agreement of Low Vision Group	Mean Agreement of Sighted Group
# 9: A user should have a 2D widget instead of a 3D widget.	2.40 [a]	2.90 [a]
# 11: A user prefers a raised line on the edge of a virtual widget rather than a grooved line.	3.90	2.90 [a]
# 17: Virtual widgets should be arranged not too from each other.	3.60	2.90 [a]
# 30: Instead of rough texture, soft texture should be assigned to the top of a widget.	3.10	2.60 [a]

[a]*Mean agreement below the score 3 refers to Strongly disagree and Disagree*

5.3. Discussion

5.3.1. Age-related individual difference study

The primary purpose was to investigate the degree to which younger and older users with low vision share a common preference for haptic user interface designs. In particular, this research was interested in statistically determining whether the two age groups show a significant difference in the agreement scores on the given list of HUI user needs. According to the results of the statistical analyses, the two age groups' overall preferences on the haptic user interface designs were not significantly different. However, the two age groups showed significantly different agreement scores on the following three HUI design ideas: "After hitting a virtual button, a user should receive verbal feedback about the button's function such as, undo, help, and find." "A user should be allowed to assign a certain point to a reference point based on a user's preference." "A user should be allowed to change the color of user interfaces such as, black and white, yellow on black, and inverted brightness."

Despite the statistically significant difference between the two age groups with regard to the three design concepts, it does not mean that the two age groups dislike the three design concepts. In fact, the two age groups' agreement scores were all above 3 and did not indicate either *Disagree* or *Strongly disagree*, supporting the idea that the two groups' preferences on the given HUI designs are not significantly different.

However, the two age groups assigned lower agreement scores (younger, mean = 2.40; older, mean = 2.90) on the following design idea: “A virtual spherical widget should not be used.” The design idea was actually devised by an older participant. The participant reported difficulty in locating such spherical shaped objects in real life. However, it turned out that younger and older groups in Study 3 generally viewed the restriction of using a particular shape of haptic widgets unnecessary. It can be interpreted that, instead of merely avoiding complex images or shapes, it is recommended to provide appropriate assistive functions or tools for users to better locate and understand such complex figures as haptic widgets.

In fact, Study 1 showed that the two age groups had no significant difference with regard to haptic capability, which supports the results of Study 3. More specifically, the magnitude estimation test in Study 1 indicated that younger and older groups with low vision had no significantly different haptic capabilities. By applying the results of Study 1 to Figure 71, it is evident that the two age groups result in being placed under the same condition associated with vision loss and touch sensitivity. Consequently, both groups might have experienced the same brain plastic change and mental models, which eventually causes both groups to indicate the same performance and behavior related to haptic technology. In that regard, it is not surprising to observe that the two age groups’ HUI user needs are not significantly different.

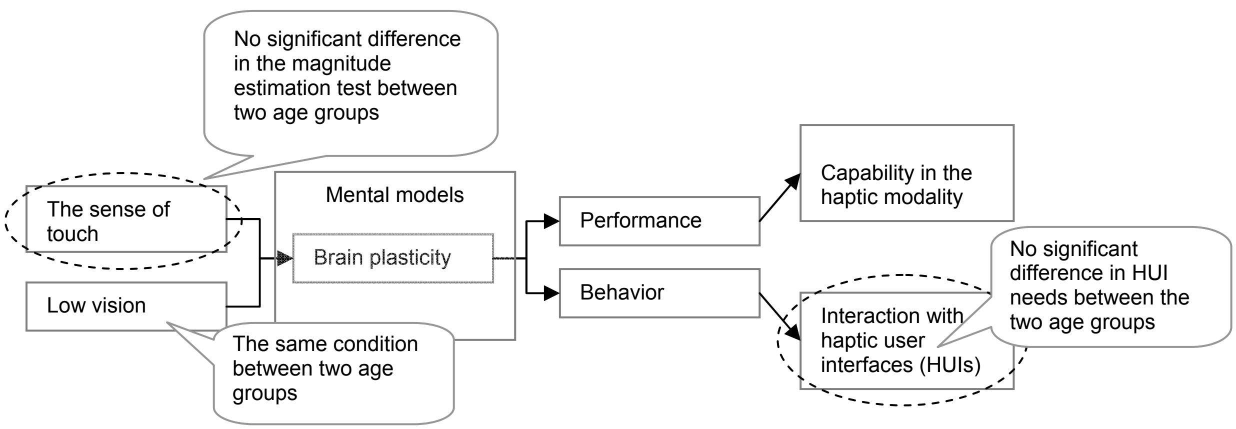


Figure 71. No significant difference of haptic capability between two age groups with low vision

However, the individual agreement analysis showed that the two age groups expressed different preferences on certain HUI designs. For example, the older group’s agreement score on the following design idea was 3.70 while the younger group’s score was 2.80: “Virtual widgets should not all be arranged on the same sagittal plane (parallel to the midline of body).” Aging is likely to influence an individual’s spatial memory (Moffat, Zonderman, & Resnick, 2009), which might lead the older group to the higher agreement score. Moffat et al. studied age differences in spatial memory, especially in a virtual environment navigation task; older participants took longer to solve a certain task, traversed a longer distance, and made more spatial memory errors than their younger counterparts. After five learning trials, the task success rate of younger participants was 86 %, but that of older participants still remained low at a 24% success rate. The present research consequently recommends that less spatially complex virtual environments be provided to older adults with low vision.

In short, the overall preference on the HUI designs was not statistically significantly different between the two age groups with low vision; however, haptic user interface designers should bear in mind that the two age groups with low vision had differing levels of preference on specific design ideas.

There was a lack of research exploring differences in HUI user needs between younger and older users with low vision. The results of the present study help to understand how much the two age groups were different in terms of their HUI needs. In addition, the haptic widgets that were used in Study 2 turned out to be useful in helping participants in Study 3 to obtain a better understanding of HUI designs.

There were limitations. The list of HUI user needs was limited to four design situations: navigation, finding objects, getting an overview, understanding an object, and discriminating between objects. Although the four situations can be regarded as fundamental UI design components for any type of device that embeds haptic technology, there is also a possibility that more various UI design components could exist. In addition, older and younger participants might have different prior experiences in using a computer in terms of frequency, purpose, software, and operating system, which possibly influenced the results of this research (e.g., user interface preference scores). This research, however, attempted to minimize the gap of computer literacy between the two age groups. Overall, most participants who were invited to the present study possessed the knowledge and ability to use computers and/or other technology (e.g., cell phone, ZoomText, and ZAWS).

Additionally, there is the likelihood that participants’ preference could change if a working prototype were given to those participants. Although the tangible prototype widgets were given to participants to help them understand future system interfaces and reduce their cognitive workload, they probably relied on their imagination somewhat. Each individual's projected image might be varying, which is also likely to influence the results of the present study.

As discussed earlier, the two age groups' overall preferences on the HUI designs were not significantly different; however, certain designs were revealed to appeal to the two age groups differently. It might be argued whether the list of haptic user interface designs in the present study covers all aspects of haptic user interface designs. However, haptic user interface designers can learn certain haptic user interfaces should be carefully designed when a target system is related to the aging issue.

The list of haptic user interface designs offers benefits to diverse groups such as designers, usability specialists, and researchers. In general, successful use of design guidelines is influenced by how they are delivered and used in an organization (or across organizations). Simply disseminating a list of design guidelines (or any type of technology or knowledge) is less likely to contribute to increasing understanding, adoption, and ongoing use of these guidelines. By considering the technology transfer concern, the present research has displayed the degree to which participants agreed with each design idea (see

Figure 72 or a full list in Appendix D). Designers, especially those with lack of experience in haptic user interface designs, can gain insight into design issues that should be carefully considered, particularly when planning and designing a haptic system for users with visual impairment. Usability specialists could modify the list to fit their organizations' needs; for example, they might want to focus only on items with a higher level of agreement by preparing the top 10 or top 20 key designs. The present research systematically grouped HUI designs into the three categories of audition, touch, and vision with relevant subcategories; usability specialists who intend to focus on the enhancement of auditory interface designs can quickly review the list under the category of audition. Researchers can also use the list of haptic user interface designs when they attempt to design a haptic system.

Haptic user interface user need	Mean agreement (1 to 5 score)	
	Low vision	Sighted
Virtual widgets should be arranged not too from each other.	3.60	2.90
A user prefers a raised line on the edge of a virtual widget rather than a grooved line.	3.90	2.90
:		:
Item # n		xx

Figure 72. A sample of mean agreement on each haptic user interface design

Based on the list of HUI designs, a working prototype could be developed and tested by individuals with low vision. Because participants rated the HUI design ideas without experiencing a working prototype, there is the likelihood that their rating scores could differ after they experience a real system.

5.3.2. *Vision-related individual difference study*

The primary purpose was to investigate the degree to which users with different vision statuses share a common preference for haptic user interface designs. In particular, this research was interested in statistically determining whether the two vision groups show a significant difference in the agreement scores on the given list of HUI user needs. According to the results of the statistical analyses, the two vision groups' overall preferences on haptic user interface designs were not significantly different. However, the individual agreement score analyses found that the preferences for certain haptic user interface designs were different between the two vision groups, the pattern of which was more complicated than that of the age-related individual-difference study (see Figure 73).

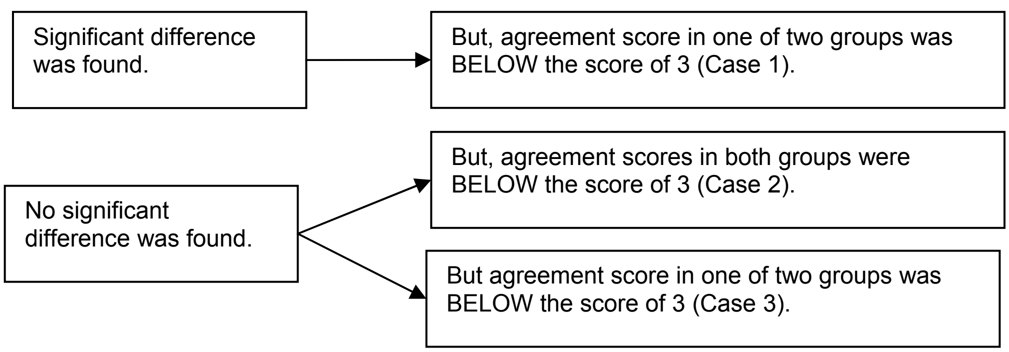


Figure 73. The comparison of two groups' preferences on each HUI user need

Case 1: The two vision groups showed significantly different agreement scores on the following HUI design idea: "A user prefers a raised line on the edge of a virtual widget rather than grooved line." However, one of the two vision groups showed a lower agreement score than 3 (low vision group = 3.9; sighted group = 2.9). The sighted group assigned a lower score, 2.9, which falls between *Disagree* and *Neutral*. Ramloll et al. (2000) reported that individuals with visual impairment are likely to rely on a tactile medium to obtain information in everyday life. Such a tactile interaction might lead the low vision group in the present study to prefer a raised line to a grooved line.

Case 2: Additionally, both vision groups assigned lower agreement scores (i.e., below 3) on the following design idea: “A user should be given a 2D widget instead of a 3D widget” (low vision group = 2.4; sighted group = 2.9). The two vision groups’ agreement scores were not statistically different. It is not uncommon that sighted people prefer a realistic 3D-based interface (e.g., computer games). A recent study reported that people with visual impairment showed successful performance when they were given a 3D haptic-embedded map compared to a 2D one (Kostopoulos et al., 2008). Thus, 3D haptic user interfaces have a potential to increase performance but also accessibility for a user with visual impairment.

Case 3: The following two HUI design ideas are examples of one of the two vision groups showing lower agreement scores (i.e., below 3) although the two vision groups’ agreement scores were not statistically significantly different. The first HUI design idea was “Virtual widgets should be arranged not too far for each other” (low vision group = 3.6; sighted group = 2.9). According to the rating scores, participants with low vision reported that they would like to have user interface components (e.g., buttons) close to each other so that they can locate them easily. On the contrary, sighted participants thought that placing virtual widgets close to each other was unnecessary. Because sighted participants can take advantage of their vision, such condensed interface designs are not preferred by them. The second HUI design idea was “Instead of a rough texture, a soft texture should be assigned to the top of a widget” (low vision group = 3.1; sighted group = 2.6). Participants with low vision wanted to have different textures at the bottom and top of virtual objects. Due to their vision limitation, they tend to depend on other sensory cues from their hands and fingers. Thus, any widgets with identical figures should have different textures (e.g., rough and soft) so that those with low vision can easily distinguish them by touch. Sighted participants, however, do not necessarily need different textures. In short, the aforementioned reasons might lead sighted participants to assign lower agreement scores.

As shown in Figure 74, vision is one of the routes that facilitate a user’s mental model construction. Individuals with total blindness cannot use this vision route. However, sighted individuals can use the vision route (e.g., visual trace and visuospatial mental images) but cannot take advantage of the brain plasticity that serves to enhance haptic capability. In addition to sighted people, those with low vision can also rely on both visual trace and visuospatial mental images. The present research initially stated that those with low vision might be influenced by brain plasticity because of their partially impaired vision and consequently, they would show enhanced haptic capability. Based on this logic, the present research postulated that the mental models of people with low vision would be different from those with sighted people and accordingly, people with low vision would have different HUI user needs. In contrast to the expectations, it was indeed revealed that sighted and low vision groups had no significantly different haptic capability. Such a result might occur due to the low level of engagement of brain plastic change. The cause of least effects of the brain plasticity is possibly associated with the notion that participants with low vision in the present study belonged to a group who insisted on relying on their vision in everyday life instead of touch. In addition, none of participants could read Braille nor were involved in any training or class to learn how to obtain information by touch. Therefore, participants with low vision may not have appreciated the importance of developing their haptic capability, which probably resulted in no significant difference in haptic capability compared to sighted participants. Study 1 demonstrated that participants with low vision had similar haptic capability to sighted participants. Given the finding of no significantly different haptic capability between the two vision groups, it is not surprising to observe that their haptic user interface needs are not significantly different either.

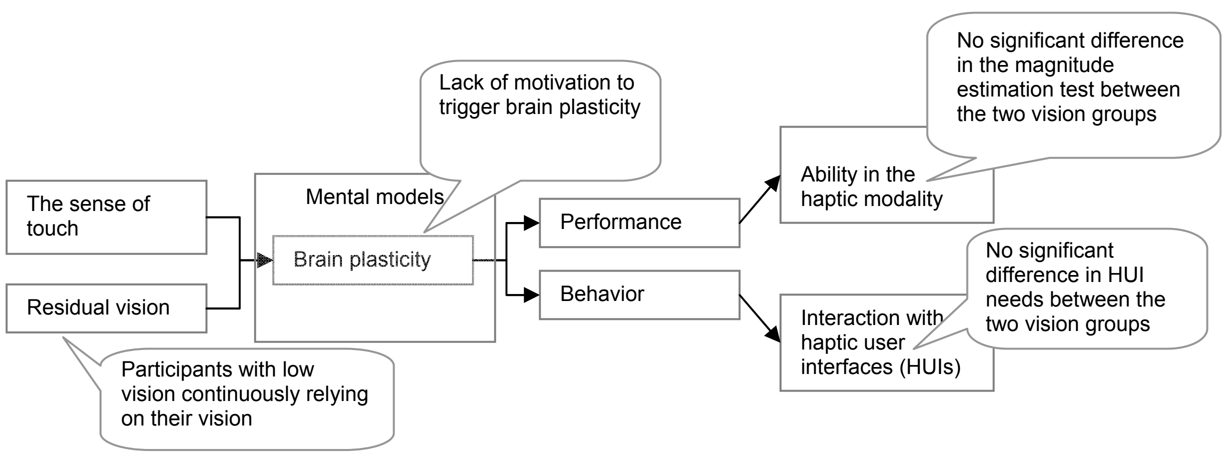


Figure 74. No significant difference in HUI user needs between the two vision groups

In short, the overall preferences for the given HUI design ideas were not statistically significantly different between the two vision groups. However, haptic user interface designers should bear in mind that the two vision groups indicated differing levels of preference for specific design ideas.

There was a lack of research exploring the differences in HUI user needs between sighted users and those with low vision. In that regard, the present research helped to understand how much the two groups were similar in terms of HUI user needs. This vision-related individual-difference study has the same strengths and limitations as the age-related individual-difference study, such as the usefulness of haptic widgets used in Study 2.

As already discussed in the age-related individual-difference study, the list of haptic user interface designs offers benefits to diverse groups such as designers, usability specialists, and researchers. The two vision groups did not show a significant difference in their preferences on haptic user interface designs. However, the two vision groups indicated different preferences for certain design ideas, such as the use of a raised line versus a grooved line. Such different design preferences between the two vision groups should be reflected in designing a haptic system.

As also discussed in the age-related individual-difference study, a working prototype could be involved in a future study to investigate how participants react to the haptic user interface designs. Such a future study would contribute to a more in-depth understanding and updating the list of HUI user needs for users with visual impairment.

CHAPTER 6. CONCLUSIONS

This final chapter discusses the summary, contributions, and implications of this research and suggests future research.

6.1. Summary

The present research attempted to shed light on two topics: (a) our understanding of individual differences among people with visual impairment (the usable accessibility study) and (b) how to enhance accessibility in existing design methods for those with visual impairments (the HUI design approach study).

The main target user group in the present study included individuals with visual impairment. There are approximately 45 million people with visual impairment worldwide, the population that increases by 1-2 million each year. Every seven minutes an individual in the U.S., for instance, becomes visually impaired. In 2008, there were nearly 1.3 million people in the U.S. who were categorized as legally blind. In fact, there are almost three times as many people who retain residual vision (or low vision) than there are people with total blindness. Furthermore, low vision is common among the elderly (aged 65 and older) because of age-related vision sensory degeneration. Of people with visual impairment, two-thirds are over the age of 65. In addition, the population of older adults with visual impairment is expected to increase. Consequently, assistive technology will play an important role in supporting those individuals in everyday life.

Today, haptic technology is often used to assist people with visual impairment to gain a better understanding of information, especially visually complex concepts. However, it has been reported that a great number of users are dissatisfied with their assistive technology applications and have discontinued the use of those applications. In particular, the adoption rate for haptic-embedded systems is low. Such dissatisfaction with and discontinuation of the use of assistive technology typically result in a waste of time, money, freedom, and reduced function in people with disabilities. Although there are diverse factors leading to such abandonment, the most significant was the failure to meet user needs.

The objective of this research was to improve the usability of a system (e.g., haptic technology) for users with low vision, especially by understanding users' individual differences. Unfortunately, a traditional approach has largely focused on accessibility, but not usability for users with disabilities. Furthermore, even prior research on accessibility and usability merely paid attention to interaction between users without and with disabilities (e.g., sighted participants and those with blindness). Therefore, very little was known concerning user interface needs of users who share the same disability category (e.g., those with low vision). In addition, the present research attempted to explore the aging effect on haptic user interface designs. Therefore, vision-related and age-related individual differences were explored in terms of users' haptic capabilities and haptic user interface needs.

The HUI design approach study aimed to develop a more accessible design method for those with visual disabilities. Conventional design methods were inapplicable to the design contexts of emerging technology, such as nongraphical user interfaces (e.g., haptic devices interacting with virtual environments) for users with visual impairment. The present study was dedicated to improving the lack of accessibility in existing design approaches by developing a more accessible PICTIVE (a participatory design method).

This research was based on an interdisciplinary approach as shown in Figure 75. In other words, a combination of theoretical perspectives in neuroscience (e.g., brain plasticity and its effect on vision/touch sensation) and psychology (e.g., direct/indirect perception and cognitive schemas) was employed to form a framework that guides the understanding of the haptic capability of users who have visual impairment and its relation to haptic user interface designs. Target users' brain activity, brain functional change, capability in the haptic modality, and preferences for HUI designs were all taken into account. Additionally, the interdisciplinary approach helped to develop a more accessible design method.

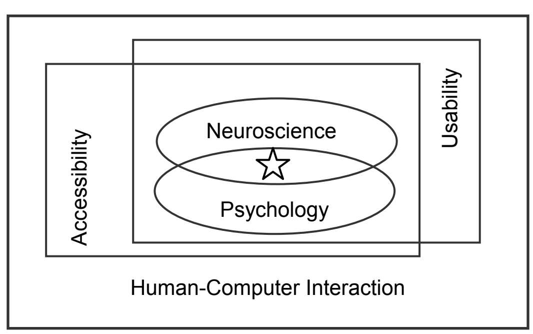


Figure 75. Interdisciplinary research approach to the usable accessibility and HUI designs

More specifically, a magnitude estimation test, a questionnaire method, and a comparison study of the original and modified PICTIVE design methods were conducted to explore the following key research hypotheses.

[Age effect] Perceived roughness would differ between age groups.

[Age effect] Haptic user interface needs would differ between age groups.

[Vision effect] Perceived roughness would differ between age groups.

[Vision effect] Haptic user interface needs would differ between vision groups.

[Original and modified PICTIVE methods] Two design methods would result in different outcomes.

The age effect was not significant. To be more precise, the haptic perception of the same objective stimulus was not significantly different between younger and older participants with low vision. In addition, the degree to which younger participants with low vision agreed with a set of haptic user interface needs was not significantly different from that of their older counterparts.

The present research found no vision effect. The haptic perception of the same objective stimulus was not significantly different between sighted participants and those with low vision. Furthermore, the present study also uncovered no significant difference between the two vision groups in terms of HUI user needs.

The effectiveness of the modified PICTIVE was investigated by comparing it with the original PICTIVE. In particular, four variables were explored, including the frequency of participants' statements, gestures, self-rated satisfaction, and time to complete a given design task. It was revealed that the two design methods produced significantly different outcomes. First, participants in the modified PICTIVE made a significantly higher number of statements than did those in the original PICTIVE. Second, participants in the modified PICTIVE showed a significantly higher number of gestures than did those in the original PICTIVE. Third, participants in the modified PICTIVE spent significantly more time because they had more design ideas to deliver than those in the original PICTIVE. Last, both groups were highly satisfied with their given design method.

Endeavors were made to explore whether younger and older users with low vision had different haptic capability. Another aspect of interest was to investigate whether those two age groups consequently tended to prefer different haptic user interface designs. Those two age groups indeed resulted in having no significantly different haptic capability, which might be due to a little brain plastic change among the age group; such a result might also cause no significantly different HUI user needs.

In addition, the aforementioned aspects of interest were explored between users with low vision and sighted users. Those two vision groups resulted in having no significantly different haptic capability, which might also be due to little or no brain plastic change among the vision group; such a result might also cause no significantly different HUI user needs as well.

Additional factors were taken into consideration to explain the results of no significant differences. The present study initially viewed participants with low vision as a group with a homogeneous condition of vision; however, it turned out that participants with low vision who were invited had different visual conditions in terms of the onset of visual impairment, which would affect brain plastic changes and mental models. A level of expertise in a certain task associated with a sense of touch might also influence younger participants' brain plastic change and performance. Older participants with low vision were actually a group who actively engaged in cognitively and physically stimulating activities, which were also likely to affect their brain plasticity and performance.

Although the data analysis of summated rating scores showed no significant difference between the two age groups and the two vision groups, the data analysis of item rating scores found that there were different preferences on certain HUIs between the two age groups and the two vision groups. Designers should reflect such heterogeneous needs when designing a haptic device. Otherwise, users are likely to be unsatisfied and abandon the system.

Besides individual differences, this research aimed to explore a more accessible design method and to investigate its effectiveness. Overall, the present research found evidence to support the effectiveness of the modified PICTIVE. Haptic prototype widgets facilitated participants' design activities.

It is possible that the study results were influenced by the ceiling effect or by unintended researcher bias. The stimuli of sandpaper samples presented in this research might have been too coarse to distinguish varying levels in haptic perception among participants, resulting in failure to identify statistically significant differences. In addition, although the researcher attempted to behave in the same way when interacting with participants in both design groups, it is conceivable that unintentional changes in the researcher's behavior could have affected the two groups' performances differently.

6.2. Contribution

There is no doubt that many Human Factors/HCI researchers and practitioners have contributed to enhancing accessibility for users with special needs. However, once the accessibility is improved, the next step is to make a product, service, or environment usable by those with disabilities. This research aimed to improve the usability of haptic-embedded assistive technology for users with visual impairments. Improving the usability of a target system for those with special needs is a critical design issue. If those with special needs are dissatisfied, the impact does not just end with the feeling of being upset or annoyed; they would be more likely to abandon a system and eventually fail to achieve independence in everyday life and at work. In particular, the present study focused on exploring what types of user interfaces would accommodate user needs successfully so that the adoption rate could increase. As a short-term contribution, this research delivered a list of HUI user needs that reflect users' individual differences in terms of age and vision. Given the present study's results, the initial conceptual framework was revised accordingly to help obtain a better understanding of low vision user group's capability in the haptic modality and its relation to HUI designs.

In addition, an accessible, participatory design approach was developed by modifying the PICTIVE design method. The modified PICTIVE design method can allow users with visual impairments to have equal power as co-designer, to get deeply involved in the whole design process, and to take an independent position on a design-related decision making process. Users with visual impairments can also obtain a better understanding of a complex system design (i.e., 3D VE haptic technology) and produce more design ideas with satisfaction. The modified PICTIVE helps to effectively elicit user needs and have those needs reflected in designs, which will eventually contribute to improving the usability of a system (e.g., accommodating diverse user needs) for those users with visual impairments.

6.3. Implications

Given the result of no significant differences in both vision- and age-related individual difference studies in terms of haptic modality and HUI user needs, the concept of inclusive design becomes more feasible. For instance, a haptic user interface designer could possibly design a haptic device that is operated with a certain range of force feedback (e.g., vibration) applicable to as many users as possible.

In addition, a variety of materials with different textures can be used in the modified PICTIVE. Study 1 demonstrated that three sandpaper samples (e.g., 120, 320, and 400 grits) were differently perceived, and they were assigned to prototype widgets (e.g., small paper boxes) that served as user interface components (e.g., buttons). By using the prototype widgets, participants had clearer images of future system interfaces. Any types of materials with different textures could also be used to improve accessibility and provide enriched design environments.

The haptic prototype widgets used in the modified PICTIVE are applicable to other participatory design approaches (e.g., ethnographic field method, cooperative design method, and contextual design method). Given the accessible design environment, users with visual impairment will become more knowledgeable about design contexts and consequently be more actively engaged in design activities. As a result, users with visual impairment can have a better chance to express their needs and have those needs reflected in user interface designs.

In addition to users with visual impairment, the haptic prototype widgets could also be a useful design tool for professionals, researchers, and students with visual impairment working in HCI and Human Factors domains. In any type of participatory design approaches, the aforementioned individuals are considered one of the critical components in the design processes because they work closely with users. Communication between users and those individuals is very important to accomplishing the participatory design. The haptic prototype widgets could enhance those individuals' communication contexts.

Such outcomes as HUI user needs and categories support a heuristic analysis method for evaluating and designing a VE-based haptic technology application. For example, the list of HUI user needs could be used as a heuristic list in the heuristic analysis process. Those lists help designers determine which usability aspects should be carefully evaluated.

The list of HUI user needs can also be used by various groups, such as designers, usability specialists, and researchers. The list contains mean agreement scores for each design idea. By using the list, designers can estimate the degree to which each design idea is supported by a population of target users in a real market. Usability specialists could modify the list to fit their organizations' needs; for instance, they could focus only on items with higher levels of agreement (e.g., *Strongly agreement* and *Agree*) by preparing the top 10 key design issues. The present study systematically grouped the HUI user needs into the three categories of audition, touch, and vision with relevant subcategories, which would facilitate the efficient use of the list. For example, usability specialists who intend to focus on the enhancement of auditory interfaces can quickly review the list under the auditory category.

Experiences from the present study led to the development of a checklist containing a list of items required, aims to be accomplished, and points to consider when using the modified PICTIVE design method with a participant who has a visual impairment.

The present research found additional gesture types and purposes in design activities among people with visual impairment. The updated list of gesture types and purposes could facilitate a gesture analysis technique, especially for users with visual impairment.

6.4. Further consideration and future research

Advancing assistive technology is not just limited to helping people with disabilities. In fact, many people without disability have problems with information technology. Therefore, research on developing and offering alternative ways of assessing technology eventually benefits everyone.

To increase the likelihood of adoption and ongoing use of a system (or a product) by as many users as possible, designers ideally prepare various versions of a product to accommodate different users' needs and elaborate on those products through usability testing. From a practical point of view, such an approach is difficult to achieve in the real world, however, because it is likely to benefit users, not a company. In general, a cost-benefit analysis is used to assess the cost involved and the estimated benefits (Wong, 2003). With regard to the return on investment for UI design and usability, Marcus (2002) constructed a quick reference to the usability statistics for value propositions. In his reference, he indicated that there are three primary aspects to be satisfied to increase the return on investment: (a) reduction in costs for development, (b) increase in revenue, and (c) enhancement of effectiveness. It is obvious that the implementation of usability would result in profits; however, the individualized design approach is rarely accepted by a company due to increased cost for development and decreased revenue.

First, since the individualized design is intended to produce various versions of a single product, it is difficult to reduce the cost for development. More specifically, those various versions are supposed to go though a series of usability tests before being released to the market, ultimately increasing the cost of development. For example, when the cost-benefit analysis is performed with regard to usability, a variety of aspects of design tasks and usability techniques are considered by breaking the tasks down into techniques, breaking the techniques down into steps, and then breaking the steps down into personnel hours and equipment costs (Bias & Mayhew, 1994). The technique is broken down into small steps, the number of hours required for each step is estimated, and then the estimated hours are multiplied by the hourly wage of each type of in-house personnel. If a company, for instance, attempts to prepare three different versions of a product to release to a market (see Figure 76), the budget for usability testing and design tasks should be increased to pay for more participants, more interview hours, more prototyping tests, and more data analyses. Even the cost to update the product after the release will increase.

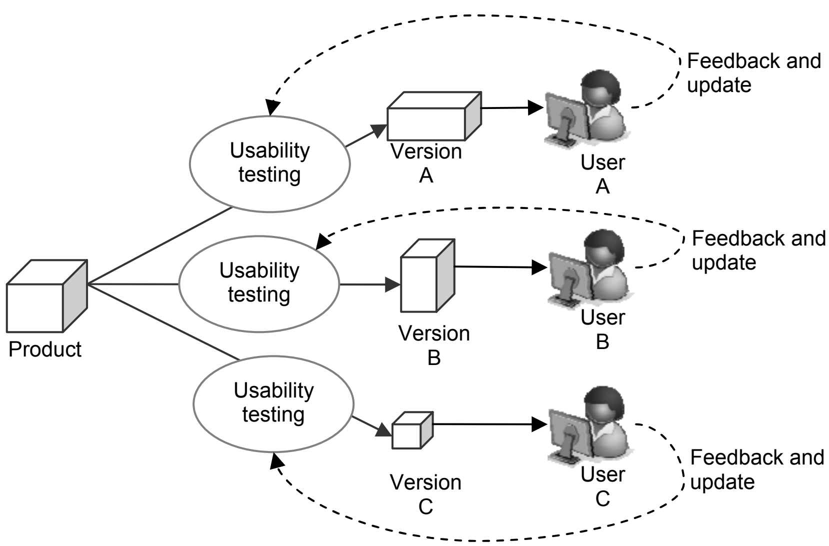


Figure 76. A more complicated process for the individualized design approach

Second, the individualized design approach for users with a particular type of disability is less likely to contribute to increasing revenue for the manufacturer. The haptic user interface designs in the present study focus on users *with* visual impairment, a population which is smaller than users *without* visual impairment. As a result, the amount of revenue would probably be small. Furthermore, the size of the population with total blindness is smaller than that of those with low vision, as discussed in the literature review section. A product that is solely designed for users with total blindness could result in much lower revenue.

Therefore, instead of such an individual design approach, universal design (UD) can be regarded as an alternative design approach that helps to resolve the low return on investment problem. UD generally aims to produce a design of products and environments to be usable by all people without the need of adaption or specialized design. UD is intended to make a single product to satisfy all users. However, the “one-product-fits-all” type of design approach is today viewed as nearly impossible to achieve (Abascal, 2002; Jhangiani, 2006; Kyoko, 2005; Newell et al., 2000; Nicolle et al., 2001).

Nevertheless, this research considers inclusive design (ID) to be a viable design approach. ID takes into account the needs of a wider range of users. In other words, ID emphasizes a product designed for the largest possible population, but not the entire population. ID can include, for example, not only sighted users but also users with various visual impairments (e.g., low vision and total blindness). Thus, it will become a more feasible design approach and is more likely to contribute to increasing the return-on-investment. Clarkson et al. (2003) also pointed out that the concept of inclusion typically increases a market size, and it can also increase return on investment. However, it should be noted that the target product in the present research is an assistive technology application that is originally designed for people with special needs. We need to note that, due to the financially related concerns, other user groups without special needs should be included. Therefore, the biggest challenge in design processes will be to determine the right balance between bringing enough benefits to a company and supporting diverse user group needs.

Furthermore, careful consideration should be give to the conflict of interest among the diverse user groups. Study 3 in the present research revealed that, overall, there was statistically no significant difference with regard to participants' needs in haptic user interface designs. However, the investigation of individual agreement scores (i.e., item rating) on each design idea revealed that user groups had different preferences for certain design ideas. Therefore, it is expected in design sessions that a group of participants suggests a design idea but the other group dislikes. The idea has, therefore, developed an interest in modeling group-based design environments to facilitate the interactive communication among sighted users and users with various visual impairments (see Figure 77). The accessible design method that the present research attempted to develop was indeed set for a micro level of design activities, in which a single user interacts with a single designer. A future research is to evolve the modified PICTIVE to develop an accessible, inclusive participatory design method. The inclusive method should facilitate user interface design activities accommodating as many users' needs as possible through group-based design decision processes.

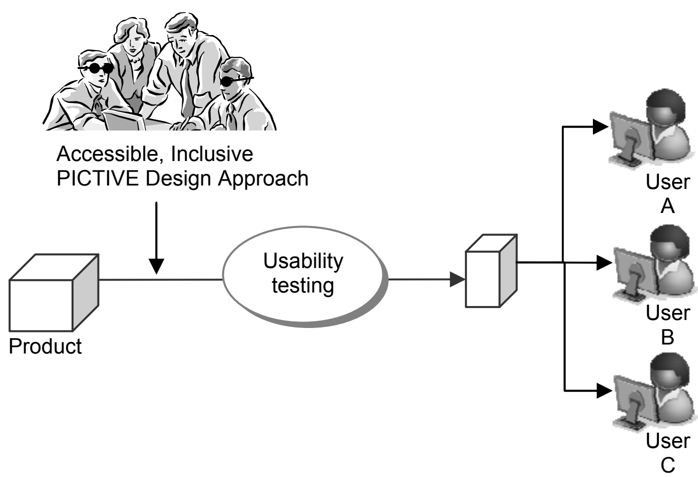


Figure 77. An accessible, inclusive PICTIVE design approach

A more detailed discussion of the development of the accessible, inclusive PICTIVE design is beyond the scope of this research and should be addressed in a future study. Such further research could be supported by the discipline of macroergonomics in order to establish a logical foundation for the study. Macroergonomics uses the sociotechnical systems approach to ensure that "the overall work system design is compatible with an organization's sociotechnical system characteristics and that the design of the subunits and components of the work system harmonize with the overall design" (Hendrick & Kleiner, 2001, p. 7). The primary concept of the accessible inclusive PICTIVE design approach should be consistent with that of macroergonomics; that is, there should be an iterative, sequential design process that emphasizes the harmony of the whole structure. The sociotechnical system should include three components: a technological subsystem (i.e., haptic technology), a personnel subsystem (i.e., participants and designers related to design tasks), and a work subsystem design (i.e., design methods). These three elements should interact with each other and with external environments (e.g., government regulations with regard to people with disabilities) so as to produce a successful design.

In addition, the future research will take into account more diverse design aspects from a national perspective. All participants in this research were Americans and accordingly produced American-centric HUI user needs. A recent cross-cultural study pointed out that different cognitive styles existed among participants from China, Korea, and America (Ying & Kun-pyo, 2008). The participants resulted in heterogeneous preferences with regard to user interface designs. User interfaces accommodating users with different cultural cognitive styles will contribute to the enhancement of the usability of a system.

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APPENDIX A: Informed consent form

Study 1: Magnitude Estimation

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent Form for Participants of Research Involving Human Subjects

Title of the Project: Usable Accessibility and Haptic User Interface Design Approach: Application of Brain Plasticity

Principal Investigator: Hyung Nam Kim, Graduate Student, ISE
Faculty Advisor: Tonya Smith-Jackson, Ph.D.

I. **The Purpose of this Research/Project**
The primary purpose of this study aims to understand the target users in terms of their abilities in the tactile modality.

II. **Procedures**
If you choose to participate in this study, we will ask you to sign one informed consent document (this document). You will keep a copy for yourself.

A pre-identified reference sample (or 'modulus') is used to develop a common scale among participants. The reference is a numeric value fixed by an experimenter. A participant is instructed to assign numeric numbers to the magnitude of given stimuli (i.e., sandpaper) as compared to the fixed value. For example, a participant will be told that if toughness of a piece of sandpaper seems twice as intense as a previous sandpaper (e.g., the first value=10), a number twice as large (e.g., the second value=20) should be assigned. The scale should have no upper limit; however, the value 0 shall be assigned only in the exceptional case, for example, when the attribute is not perceived. Participants use round numbers such as 5, 10, and 15 in the scaling technique. In addition, participants will be allowed to move their index finger around and touch the sandpaper all directions. An experimenter will help them to locate the sandpaper if needed. Participants are also permitted to touch the assigned sandpaper sample as often they want. Participants who retain vision such as low vision are allowed to use their vision. This data will be used for our research purposes, that is, to improve the design method of haptic assistive technology. We would like to get your honest and direct feedback about your experience. Participation in this study will take about 1 hour.

III. **Risks**
No more than minimal risks are introduced by participation in this study. The only identifiable loss is related to the inconvenience that may be introduced by taking time out of your schedule to participate. We will make every effort to avoid interfering with your daily schedule. Actual participation in this study is not likely to cause any harm.

IV. **Benefits of the Project**
You will not gain any direct benefits as a result of your participation, but I am aware of the published findings of this study should have an important impact on assistive technology by providing a method for presenting information non-visually to individuals with visual impairment.

V. **Extent of Anonymity and Confidentiality**
We assure confidentiality to all participants of the study. However, anonymity cannot be guaranteed, because we will need to have your signatures on the Informed Consent document. However, this document will be kept in a locked cabinet for 5 years and your name will not be released. At the end of the 5-year period, we will destroy the documents. Your name will not be associated with the content of this observation, but you will be assigned a three-digit number to protect your privacy. Your number is ____, and this number is also on your folder.

This session will be videotaped to ensure we collect conversations, design ideas, and gestures you may produce while interacting. Please do not refer to each other by name in the videotapes. We will refer to you by our participant number. The videos will be shown to other researchers who are interested in design research. If you feel uncomfortable having your face shown on a video, please sign the appropriate area at the end of the form.
All data will be collected by the researchers only. No one other than the researchers will have access to the data, unless it is aggregated first. All responses will be coded so as not to include the name of the participant. The information you provide will have your name removed and only a three- digit participant number will identify you during analyses and any written reports of the research.

This study is being conducted for educational and research purposes and the resulting data and interpretations will also be the part of the researchers' academic work. Consistent with these academic purposes, any results would be freely publishable. However, to protect your identity, neither personal nor institutional names nor site names or distinguishing information will be used in any published works.

VI. **Compensation**
You will be compensated at the rate of $10/hour.

VII. **Freedom to Withdraw**
Participation in the study is voluntary and the decision about whether you wish to participate is strictly your own. You may discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled. Withdrawal from the study will not result in any adverse effects.

VIII. **Approval of Research**
This research project has been approved by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering (College of Engineering).

__________________ ______________________
IRB Approval Date IRB Expiration Date

IX. **Participant's Responsibilities**

Upon signing this form below, I agree to participate in this study. I have no restrictions to my participation in this study.

X. **Participant's Permission**

I have read and understood the Informed Consent and conditions of this study. All of my questions have been answered. I agree to participate in this project.

______________________________ ______________________
Participant's Signature Date

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I consent to have my video shown as long as my name is not used in the video, nor given to other researchers (confidentiality). All of my questions have been answered. I consent to the sharing of videos with researchers other than those involved in the study.

______________________________ ______________________
Participant's Signature Date

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I DO NOT consent to have my video shown. I understand my face will be scrubbed from the video and the camera will minimize focusing on my face during the entire session. All of my questions have been answered. I DO NOT consent to the sharing of videos with researchers other than those involved in the study.

______________________________ ______________________
Participant's Signature Date

Should I have any questions or concerns about this research or its conduct, I may contact:

Dr. Tonya Smith- Jackson Email:smithjack@vt.edu Phone: (540) 231-4119

Dr. David M. Moore, Email: moored@vt.edu Phone: (540) 231-4991
Chair, IRB

Study 2: User Needs Elicitation Method

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent Form for Participants of Research Involving Human Subjects

Title of the Project: Usable Accessibility and Haptic User Interface Design Approach: Application of Brain Plasticity

Principal Investigator: Hyung Nam Kim, Graduate Student, ISE
Faculty Advisor: Tonya Smith-Jackson, Ph.D.

I. **The Purpose of this Research/Project**
The primary purpose of this study is to develop a touch-based, low-fidelity prototyping technique to facilitate user needs elicitation.

II. **Procedures**
If you choose to participate in this study, we will ask you to sign one informed consent document (this document). You will keep a copy for yourself.

We will then begin designing a haptic user interface along with a designer. A video camera will be used to record the design session. Faces of participants will be scrubbed from the video so we can show participants' hands/gestures. After you complete the design, you will be asked to complete a questionnaire. This data will be used for our research purposes, that is, to improve the design method of haptic assistive technology. We would like to get your honest and direct feedback about your experience. Participation in this study will take about 1 hour.

III. **Risks**
No more than minimal risks are introduced by participation in this study. The only identifiable loss is related to the inconvenience that may be introduced by taking time out of your schedule to participate. We will make every effort to avoid interfering with your daily schedule. Actual participation in this study is not likely to cause any harm.

IV. **Benefits of the Project**
You will not gain any direct benefits as a result of your participation, but I am aware of the published findings of this study should have an important impact on assistive technology by providing a method for presenting information non-visually to individuals with visual impairment.

V. **Extent of Anonymity and Confidentiality**
We assure confidentiality to all participants of the study. However, anonymity cannot be guaranteed, because we will need to have your signatures on the Informed Consent document. However, this document will be kept in a locked cabinet for 5 years and your name will not be released. At the end of the 5-year period, we will destroy the documents. Your name will not be associated with the content of this observation, but you will be assigned a three-digit number to protect your privacy. Your number is ____, and this number is also on your folder.

This session will be videotaped to ensure we collect conversations, design ideas, and gestures you may produce while interacting. Please do not refer to each other by name in the videotapes. We will refer to you by our participant number. The videos will be shown to other researchers who are interested in design research. If you feel uncomfortable having your face shown on a video, please sign the appropriate area at the end of the form.
All data will be collected by the researchers only. No one other than the researchers will have access to the data, unless it is aggregated first. All responses will be coded so as not to include the name of the participant. The information you provide will have your name removed and only a three- digit participant number will identify you during analyses and any written reports of the research.

This study is being conducted for educational and research purposes and the resulting data and interpretations will also be the part of the researchers' academic work. Consistent with these academic purposes, any results would be freely publishable. However, to protect your identity, neither personal nor institutional names nor site names or distinguishing information will be used in any published works.

VI. **Compensation**
You will be compensated at the rate of $10/hour.

VII. **Freedom to Withdraw**

Participation in the study is voluntary and the decision about whether you wish to participate is strictly your own. You may discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled. Withdrawal from the study will not result in any adverse effects.

VIII. **Approval of Research**
This research project has been approved by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering (College of Engineering).

________________ _____________________
IRB Approval Date IRB Expiration Date

IX. **Participant's Responsibilities**

Upon signing this form below, I agree to participate in this study. I have no restrictions to my participation in this study.

X. **Participant's Permission**

I have read and understood the Informed Consent and conditions of this study. All of my questions have been answered. I agree to participate in this project.

___________________________ ___________________
Participant's Signature Date

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I consent to have my video shown as long as my name is not used in the video, nor given to other researchers (confidentiality). All of my questions have been answered. I consent to the sharing of videos with researchers other than those involved in the study.

___________________________ ___________________
Participant's Signature Date

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I DO NOT consent to have my video shown. I understand my face will be scrubbed from the video and the camera will minimize focusing on my face during the entire session. All of my questions have been answered. I DO NOT consent to the sharing of videos with researchers other than those involved in the study.

___________________________ ___________________
Participant's Signature Date

Should I have any questions or concerns about this research or its conduct, I may contact:

Dr. Tonya Smith- Jackson Email:smithjack@vt.edu Phone: (540) 231-4119

Dr. David M. Moore, Email : moored@vt.edu Phone: (540) 231-4991
Chair, IRB

Study 3: Individual Differences of Haptic User Interfaces

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent Form for Participants of Research Involving Human Subjects

Title of the Project: Usable Accessibility and Haptic User Interface Design Approach: Application of Brain Plasticity

Principal Investigator: Hyung Nam Kim, Graduate Student, ISE
Faculty Advisor: Tonya Smith-Jackson, Ph.D.

I. **The Purpose of this Research/Project**
The primary purpose of this study aims to understand the target users in terms of their needs for haptic user interfaces.

II. **Procedures**
If you choose to participate in this study, we will ask you to sign one informed consent document (this document). You will keep a copy for yourself.

Participants will be asked to complete a questionnaire that includes a set of statements with regard to haptic user interfaces. While filling the questionnaire out, the participants are permitted to manipulate a given prototype. This data will be used for our research purposes, that is, to improve the design method of haptic assistive technology. We would like to get your honest and direct feedback about your experience. Participation in this study will take about 1 hour.

III. **Risks**
No more than minimal risks are introduced by participation in this study. The only identifiable loss is related to the inconvenience that may be introduced by taking time out of your schedule to participate. We will make every effort to avoid interfering with your daily schedule. Actual participation in this study is not likely to cause any harm.

IV. **Benefits of the Project**
You will not gain any direct benefits as a result of your participation, but I am aware of the published findings of this study should have an important impact on assistive technology by providing a method for presenting information non-visually to individuals with visual impairment.

V. **Extent of Anonymity and Confidentiality**
We assure confidentiality to all participants of the study. However, anonymity cannot be guaranteed, because we will need to have your signatures on the Informed Consent document. However, this document will be kept in a locked cabinet for 5 years and your name will not be released. At the end of the 5-year period, we will destroy the documents. Your name will not be associated with the content of this observation, but you will be assigned a three-digit number to protect your privacy. Your number is ____, and this number is also on your folder.

This session will be videotaped to ensure we collect conversations, design ideas, and gestures you may produce while interacting. Please do not refer to each other by name in the videotapes. We will refer to you by our participant number. The videos will be shown to other researchers who are interested in design research. If you feel uncomfortable having your face shown on a video, please sign the appropriate area at the end of the form.
All data will be collected by the researchers only. No one other than the researchers will have access to the data, unless it is aggregated first. All responses will be coded so as not to include the name of the participant. The information you provide will have your name removed and only a three- digit participant number will identify you during analyses and any written reports of the research.

This study is being conducted for educational and research purposes and the resulting data and interpretations will also be the part of the researchers' academic work. Consistent with these academic purposes, any results would be freely publishable. However, to protect your identity, neither personal nor institutional names nor site names or distinguishing information will be used in any published works.

VI. **Compensation**
You will be compensated at the rate of $10/hour.

VII. **Freedom to Withdraw**

Participation in the study is voluntary and the decision about whether you wish to participate is strictly your own. You may discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled. Withdrawal from the study will not result in any adverse effects.

VIII. **Approval of Research**
This research project has been approved by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering (College of Engineering).

IRB Approval Date ______ IRB Expiration Date ______

IX. **Participant's Responsibilities**

Upon signing this form below, I agree to participate in this study. I have no restrictions to my participation in this study.

X. **Participant's Permission**

I have read and understood the Informed Consent and conditions of this study. All of my questions have been answered. I agree to participate in this project.

Participant's Signature ______ Date ______

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I consent to have my video shown as long as my name is not used in the video, nor given to other researchers (confidentiality). All of my questions have been answered. I consent to the sharing of videos with researchers other than those involved in the study.

Participant's Signature ______ Date ______

I have been made aware that the video and audio recordings will be shared with other researchers outside of this study. I DO NOT consent to have my video shown. I understand my face will be scrubbed from the video and the camera will minimize focusing on my face during the entire session. All of my questions have been answered. I DO NOT consent to the sharing of videos with researchers other than those involved in the study.

Participant's Signature ______ Date ______

Should I have any questions or concerns about this research or its conduct, I may contact:

Dr. Tonya Smith- Jackson Email:smithjack@vt.edu Phone: (540) 231-4119

Dr. David M. Moore, Email : moored@vt.edu Phone: (540) 231-4991
Chair, IRB

APPENDIX B: Questionnaire to measure the effectiveness of a method

Evaluation of user needs elicitation method

Section 1: Introduction

You are invited to participate in a design session for a haptic technology. The haptic technology is to facilitate people with visual impairment in obtaining visually complex information, which is still under construction. We need your feedback as future users.

Thank you for being willing to help us with this. It takes about 30-45 minutes to do the design practice. At the end, you will also be asked to evaluate the design procedure that guides you. If you want, you can use other types of questionnaires such as computer-supported questionnaires and Braille questionnaires. Please ask an investigator or designer in the room.

Section 2: Instructions to answer

A single item consists of three components that are represented through three lines. First, you will see a statement in the first line. Please read it. You are supposed to make a decision whether you strongly disagree, disagree, neutral, agree, or strongly agree.

In the second line, you will see a scale with 5- point anchors. From left to right, the first circle refers to strongly disagree. The second is disagree. The third is the neutral. The fourth is agree. The last circle, 5th circle, refers to strongly agree. Please, mark one of them. Multiple marks are unacceptable.

In the last line, the 3rd line, you are allowed to make a comment regarding the given statement. Please, feel free to provide your thoughts. We would like to assure you that there are no incorrect answers. We would appreciate any feedback from you.

A total of twelve items are listed from page 2 to page 4.
If you have any questions, please raise your hand.

- Please, wait until you are allowed to go to the next page to begin –

1. The procedure helps me describe my job to the designers.

Strongly Disagre	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

2. The design procedure helps me change the design to meet my needs.

Strongly Disagre	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

3. I believe that the people who were from the software product design group understood what I was trying to show them.

Strongly Disagre	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

4. I feel free to express myself.

Strongly Disagre	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

5. I am satisfied with this means of obtaining my input.

○—○—○—○—○

Strongly Disagre | Disagree | Neutral | Agree | Strongly Agree

6. The procedure was enjoyable.

○—○—○—○—○

Strongly Disagre | Disagree | Neutral | Agree | Strongly Agree

7. The procedure was interesting.

○—○—○—○—○

Strongly Disagre | Disagree | Neutral | Agree | Strongly Agree

8. The procedure was valuable.

○—○—○—○—○

Strongly Disagre | Disagree | Neutral | Agree | Strongly Agree

9. I hated being videotaped.

Strongly Disagre	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

10. What was the best aspect of the procedure? Several answers are possible.

APPENDIX C: Gesture purposes and gesture types in design activity

Purpose of gesture in design activity	**Type of gesture**																
	Relocation of an object	Draw line with finger	Beat (touch)	Lateral motion	Pressure	Static contact	Unsupported holding	Enclosure	Contour following	Finger-to-body	Finger-to-finger	Finger-to-hand movement	Topic gesture (depictive)	Pointing	Beat series (untouched)	Beat (untouched)	Stereotypical hand signal (emblem)
contrast ideas																	
contrast objects																	
contrast persons																	
contrast places																	
depict performance																	
highlight some part of the sentence																	
list items																	
refer to a body part																	
refer to an idea																	
refer to an object																	
refer to a person																	
refer to a place																	
refer to sound																	
refer to time																	
show distance																	
show shapes																	
show sizes																	
understand an object																	
refer to sound																	
refer to time																	

Description of gesture types

Gesture types	**Description**
Relocation of an object:	The location of an object is changed by the hands and fingers.
Draw line with finger:	A participant uses a finger to describe a certain artifact by drawing a line on a table (or depict a figure).
Beat (touch):	Short, quick movements of the hands that coordinate with the rhythm of speech and serve to emphasize or punctuate speech; however, contact is made with an artifact, such as a table.
Lateral motion:	Finger(s) are touching a surface of an object and moving from left to right or vise versa.
Pressure:	Finger(s) are pushing an object firmly against a surface.
Static contact:	Finger(s) are touching a surface.
Unsupported holding:	An object is placed in the hand in which its weight is held and it is prevented from falling.
Enclosure:	An object is surrounded by the hand.
Contour following:	Fingers or the hand is following the shape of the outer edges of something.
Finger-to-body:	Stroking of one’s body with his or her fingers.
Finger-to-finger:	Stroking of one’s fingers with the other fingers.
Finger-to-hand movement:	Stroking of one’s fingers or hand with the other fingers and/or hand; however, no communication is involved.
Finger-to-finger adaptor:	Stroking of one’s fingers by the other fingers; however, no communication is involved.
Body-focused adaptor:	Any movement of the hands or arms that is in relation to one’s own body (scratching, rubbing thighs) that serves no communicative function.
Object-focused adaptor:	Any movement of the hands that contacts another object (tapping a pen, arranging one’s clothes or hair) that serves no communicative function.
Topic gesture (depictive):	Any hand or arm movements that depict some aspect of the topical content of a conversation.
Adaptors (untouched) :	Any movement of the arms, hands, fingers not serving any apparent communicative function.
Pointing:	Hand movements that refer to the addressee and provide no information about the topic, but serve several conversation functions.
Beat series (untouched) :	A series of beat movements done in rapid succession so that the onset or termination of the individual beats cannot be distinguished.
Beat (untouched) :	Short, quick movements of the hands that coordinate with the rhythm of speech and serve to emphasize or punctuate speech.
Stereotypical hand signal (emblem) :	Any stereotypical hand signal used to convey meaning in nonspeaking contexts.

Description of gesture purposes

Gesture Purposes	Definition
contrast ideas:	To set in opposition in order to show differences among ideas.
contrast objects:	To set in opposition in order to show differences among objects.
contrast persons:	To set in opposition in order to show differences among persons.
contrast places:	To set in opposition in order to show differences among places.
depict performance:	To describe the act of performing; for example, the use of a product, daily activities, and so forth.
highlight an idea:	To show emphasis while speaking.
list items:	To make a list.
refer to a body part:	To direct to a body part for information.
refer to an idea:	To direct to the idea stated earlier.
refer to an object:	To direct to an object, for example, a prototype artifact.
refer to a person:	To direct to a person, for example, a designer, a participant, or others.
refer to a place:	To direct to a place.
refer to sound:	To direct to a sound, such as a nonspeech sound like clicking.
refer to time:	To direct to time.
show distance:	To describe the length of a line segment joining two points.
show shapes:	To describe the surface configuration of an object.
show sizes:	To describe the physical dimensions of an object.
understand an object:	To comprehend the nature of an object by close contact.

APPENDIX D: Haptic user interface needs

Age-related individual difference study (younger group with low vision versus older group with low vision)

Category	Subcategory	Condition	User needs	Description	Degree of agreement	
					Younger	Older
Audition	Speech	Besides a main menu bar and menu, a virtual button can be embedded in the 3D virtual space. A user wonders whether he or she clicked the right one.	After hitting a virtual button, a user should receive verbal feedback about the button's function: such as "Undo", "Help", “Find”, and so on.	The system keeps a user informed of the current situation through appropriate feedback within a reasonable time.	4.7 (0.48)	3.9 (0.88)
		A user would like to be briefly introduced with regard to the whole structure before performing any activity.	A system should verbally describe the structure of the interfaces (e.g., location of buttons or objects) via a natural human voice instead of a synthesized voice.	Building a mental image of interfaces in the 3D virtual space will contribute to a user's space perception.	4.1 (0.74)	3.7 (0.82)
		A user is seeking a certain widget such as a reference point. A user would like to rely on a sense of hearing instead of other senses, such as a sense of touch or vision.	If a user prefers to depend on auditory feedback, speech sounds should describe a route from a reference point to a certain point (e.g., 3D virtual space boundary, reference point).	A user's space perception is efficiently enhanced by accommodating the user's personal preference.	4.3 (0.95)	3.8 (0.63)
		A user spends a lot of time adapting to different tones of a system’s speech sounds.	Speech sounds should be tonally consistent.	Users should not have to wonder whether different words, situations, or actions mean the same thing.	4.3 (0.48)	4.5 (0.53)
		A user would like to receive responses after completing an action.	A user’s performance should always be confirmed through a speech sound: for example, "It is successfully completed" in a dialog box.	The confirmation message contributes to a user's error prevention.	4.1 (0.99)	4.2 (0.42)
	Non- speech	A user lost contact while following the contour of a virtual widget (e.g., a button).	A system should generate a non-speech sound (e.g., beeping) once a user loses contact while following the contour of an object.	Non-speech sounds immediately inform a user of the lost contact.	4.0 (0.47)	4.3 (0.48)
Touch	Accuracy	A user often makes mistakes in computing; for example, a user ends up clicking "OK" on the dialog "Are you sure you would like to quit the program without saving?” A user does not pay attention to the dialog because he or she clicks “OK” too often.	A reset or undo button should be available. A user should be able to escape from an unwanted status by using a reset or undo button. The reset or undo button lets a user start from the beginning.	By hitting a reset or redo button, a user can work his or her way back to the point before the mistake was made. As a result, a user’s feeling of being in control will also increase.	4.5 (0.85)	4.0 (1.41)
		A user touches an unwanted button in the virtual space that is located next to a wanted button.	A virtual button should be sturdy.	Sturdy buttons prevent a user from accidently pushing an unwanted button that is placed close to a wanted button.	4.2 (0.92)	4.4 (0.52)
		A user gets lost while navigating or finding certain widgets. The user does not know where a reference point is located from the user's current position. The user decides to ask the system for	A user's 3D virtual pointer is automatically guided by a system toward a previous position or a reference point upon the user's request.	Automatic movement will ease a user’s cognitive workload.	4.0 (0.82)	3.7 (0.82)

	help in order to return to a reference point.				
	A user gets lost while navigating or finding certain objects. The user does not know where a reference point is located from the user's current position. The user decides to ask the system for help in order to return to a reference point.	When a user's virtual pointer is guided by a system, different routes should be available for a user to choose, based on duration and distance; for instance, a user can either directly jump to the reference point or follow his or her track.	The choice of following in his or her track back contributes to a user's space perception. The choice of directly jumping helps to save users' time.	4.2 (1.23)	3.9 (0.88)
	A user is likely to lose contact with a virtual widget while following its contour.	When a user loses contact with a virtual widget (e.g., contour following), a context menu should be available to ask the user whether the user would like to rely on automatic guidance to go back to the previous position of the object.	Such an auto movement will help a user concentrate on his or her primary work.	4.1 (0.88)	4.2 (0.42)
	A user gets lost while navigating or finding certain objects.	A reference point should be available in the 3D virtual space.	A reference point serves as a "lighthouse" for a user in the 3D virtual space.	4.2 (0.92)	3.9 (0.74)
	A user gets lost while navigating or finding certain objects.	A user should be allowed to assign a certain position as a reference point based on the user's preference.	A reference point serves as a "lighthouse" for a user in the 3D virtual space.	4.5 (0.71)	3.5 (0.85)
	A reference point is located differently over subpages (or virtual sub spaces).	A reference point should be located at the same place through all subpages. A system should provide consistency in user interfaces throughout the whole system.	A reference point serves as a "lighthouse" for a user in the 3D virtual space.	4.2 (0.79)	4.4 (0.85)
	A user chooses to rely on a programmed movement of the virtual pointer that guides him or her toward a certain virtual widget. When a user touches a virtual pointer to the widget, he or she realizes that the widget is not what the user wanted.	A user should be given a confirmation message that asks whether the user wants to stay or leave (e.g., going back to the reference point or previous point). No activity should be allowed until the confirmation message is cleared.	The dialog box enables a user to control how to carry out an action. It contributes to a user's error prevention.	4.0 (1.15)	3.8 (0.63)
Force bandwidth	A user's virtual pointer moves around to get an overview of the virtual environment.	A user should experience haptic feedback when his or her virtual pointer is hovering over widgets in the virtual space. Feedback is given upon a user's request.	A novice user is not good at operating the system and exploring the virtual space. Additional feedback will enhance the user's operation.	4.3 (0.67)	4.1 (0.32)
Sensing acuteness	Besides a main console (e.g., a menu bar and toolbar), a 3D virtual button is often embedded in a 3D virtual space. Such a user interface element provides a user a simple way to trigger an event. A user switches a button from 'on' to 'off' or vise versa.	When a push button is switched from 'on' to 'off' or vise versa, different textures should be assigned to the button.	In graphical user interfaces, activating a button makes its associated content visible and the button itself usually becomes highlighted with different colors to distinguish it from other, inactive ones. In haptic user interfaces, different textures should be used	3.1 (1.20)	3.9 (0.74)

				instead of different colors.		
		How should it be designed to effectively deal with disabled buttons/menus/taps that are not supposed to allow double clicks?	After a push button is pushed down, the push button should return to the original height.	Disabled buttons can still be used as reference points for users with visual impairments; it is a critical design issue.	3.9 (0.74)	3.3 (1.16)
		All virtual buttons are identical in terms of size, regardless of function. A user gets confused and should carefully pay attention to distinguish them. Even a returning user must put considerable effort into recall.	Virtual buttons in the 3D virtual space (besides a main menu bar) should be grouped and separately placed according to their size. Different aspects (e.g., functions) of virtual buttons should be indicated by different size and/or shape.	Using different size and/or shape for different functions of buttons can contribute to a user's ease of understanding.	3.9 (1.20)	3.8 (0.79)
		A user touches virtual buttons in the 3D virtual space.	A convex (bulging outward) button should be used rather than a concave (inward-curving) button.	A convex type widget in the virtual space increases the possibility of being detected by a user's touch.	3.7 (1.42)	3.8 (0.92)
		A user spends a lot of time touching and understanding virtual key pads that are placed in the 3D virtual space.	When virtual button numbers are in ascending order (such as 1, 2, and 3), increasing toughness of textures should be assigned to the buttons respectively.	A user should not need to put a lot of efforts into remembering information and/or content presented by a system. Tactile clues will ease the user's memory load.	3.6 (1.17)	3.9 (1.10)
		A user gets lost while navigating or finding certain objects.	To build multiple reference points, each reference point should be unique in terms of texture, shape, sound, size,	A reference point serves as a “lighthouse” for a user in the 3D virtual space.	4.4 (0.70)	4.0 (0.47)
		A user's virtual pointer explores the space by touching different widgets. However, a user is likely to miss 2D virtual widgets.	Virtual objects should be represented in 3D instead of 2D.	3D figures are more distinctive and easier to detect than 2D.	3.8 (1.23)	3.3 (1.06)
		If virtual widgets are widespread, a user is likely to miss some of them.	Virtual objects should be arranged close to the midline of a user’s body.	In general, users with visual impairments tend to focus in front of the body because they have a vision field that is limited to the center.	3.6 (0.97)	3.7 (0.67)
		When a user interacts with a set of virtual objects, the user typically tends to scan a working area by moving from left to right and vice versa instead of up and down.	3D virtual objects should be arranged on a horizontal line instead of a curvy line.	Systemically displaying widgets, such as having all on a horizontal line, is likely to help a user successfully locate all objects by moving horizontally.	3.9 (1.2)	4.3 (0.48)
		A user with Carpal Tunnel Syndrome may have abnormal touch sensitivity.	Force feedback (e.g., vibration) should not be solely used. A user should be given a means to customize a system. Multimodal feedback methods (e.g., visual, sound, haptic feedbacks) should be available upon a user's request.	Force feedback (e.g., vibration) should not be solely used because a user might have Carpal Tunnel Syndrome.	4.5 (0.85)	4.2 (0.92)
		A spherical shaped widget is difficult for a user to understand by touch in the real world.	A virtual spherical widget should be avoided.	The system should communicate with a user through concepts familiar to the user, rather than system-oriented one. User interfaces should follow a user's real-world conventions, making information appear in a natural and logical order.	2.4 (0.52)	2.9 (0.88)

		The user's virtual pointer is approaching the boundary of the 3D virtual space.	A system should generate vibration with speech sounds when a user's virtual pointer touches the boundary of the 3D virtual space.	A combination of two different sensory modalities can increase a user's chance of being informed about a situation.	3.8 (0.92)	4.1 (0.32)
		A user wants to save time and efforts when finding a place or object in the 3D virtual space.	There should be a search function. A user types a place to go or objects to find. A system then verbally or physically guides the user toward the target.	A search function can save a user's time and effort.	4.1 (0.57)	4.1 (0.57)
		A user is likely to become confused as to the degree to which a slider (or a clock type) button is moved.	A push type button should be used in the 3D virtual space because it is the most preferred design compared to others (a switch up/down button and a clock type button).	A push button shows only two statuses—on and off—making it easy for a user to understand the status.	3.9 (0.88)	3.5 (1.27)
	Workspace size	A user's virtual pointer quite often touches a virtual menu bar by mistake. The menu bar interrupts the virtual pointer's movement. A user's virtual pointer results in a limited range of movement in the 3D virtual space.	If a virtual menu bar is implemented, a user should be allowed to rearrange it in a way the user thinks is more suitable and easy to navigate around in the 3D virtual space. A user should be able to drag and drop it to change its position.	A user will have enough space to navigate and not bump into the menu bar.	4.4 (0.97)	3.5 (1.18)
		A user gets lost and wanders away from a working area. The user has no idea of his or her location in the virtual space.	A 3D virtual space should have a boundary.	Graphic user interfaces have a container, that is, window. A sighted user is able to see the window through vision. A pointer's location is identified whether it is inside or outside of the window. Haptic user interfaces have a virtual boundary.	4.1 (0.57)	4.3 (0.48)
		A user navigates in the 3D virtual space.	Once a system is activated, it should provide a user with a chance to perceive a 3D virtual space size by guiding a user to touch, follow, and feel the boundary. A user should have force feedback (for example, vibration or locking a virtual pointer move).	In this way, a user's space perception will be enhanced. Space perception provides cues, such as depth and distance, that are important for movement and orientation to the environment. As a result, the user becomes aware of the relative position of his or her virtual pointer.	3.8 (0.92)	4.0 (0.82)
		A virtual space is large. A user keeps moving to find a certain object.	A small-sized virtual space should be provided to a user.	It is a challenge for a user to locate objects in the large virtual space.	3.5 (1.08)	3.3 (0.82)
vision	Icons					
		Widgets in the 3D virtual space are arranged to be overlapped so that multiple objects look like a single object.	Virtual widgets should not all be arranged on the same sagittal plane (parallel to the midline of body).	There are two identical widgets. If a widget is located right behind another widget, a user gets confused and considers them as a single widget.	2.8 (1.14)	3.7 (0.95)
		Widgets in the 3D virtual space share the same color or a combination of less distinctive colors.	The color should be changeable to black and white, yellow on black, and inverted brightness.	The clarity of contents presented in the 3D virtual space generally contributes to a user's easier viewing and reduced eyestrain.	4.3 (0.95)	3.3 (1.16)
		Small widgets are difficult for a user to detect.	Extremely small widgets should be avoided	Making widgets easy to detect is critical to user interface designs.	3.3 (1.25)	4.3 (0.48)

Vision /Audition	Icons	While a user tries to find a certain virtual widget (menu or other objects in the virtual space), there is a possibility that the user fails to locate it. However, a user may desire to continue looking instead of going back to a reference point.	A system should be able to scan any virtual widgets (e.g., user interface components and any other objects) near a user's virtual pointer and update the user on their locations (e.g., overview).	Unless a user wants to get back to a reference point, a user prefers to keep moving around to find a target.	4.4 (0.52)	4.1 (0.57)
	Menus	A user should trigger an event.	Shortcut keys on a keyboard should be set as primary tools to control or play with content in the 3D virtual space instead of manipulating menus on a screen.	A computer keyboard is easy for a user with visual impairments to operate rather than menus on a screen.	3.2 (1.23)	3.5 (0.71)
		A user is not good at spelling.	A system should provide a spelling checker.	A spell checker flags words in a search box that are not spelled correctly.	4.1 (0.74)	3.6 (1.07)
	Pointers	A user controls a system's input device (such as mouse) that is associated with a virtual pointer. It is not easy for a user to follow a fast move of a 3D virtual pointer on the screen.	A user should be allowed to adjust a 3D virtual pointer speed.	Adjusting the virtual pointer speed is a necessity for certain users. If a user wants to play a fast-paced application with a lot of dynamic movements, a faster pointer speed is desired. Sometimes, a user plays with a delicate move.	4.5 (0.71)	3.8 (1.23)
	Windows	A boundary is less noticeable. A user is likely to miss the boundary in the 3D virtual space. A user's virtual pointer moves through it and the user gets lost. A user likes to be informed visually before bumping into the virtual boundary.	A 3D virtual space should have a boundary with colorful spots.	Color helps a user to easily recognize the boundary.	3.3 (1.34)	3.0 (1.15)
		Text or an image is presented to a user. However, the sentence is too long to be shown in a given space, or the image is too big to fit in the virtual working area.	The whole widget or text should be shown within a working space. It should be ensured that, even if the image of a widget (or text) is magnified, the entire image (sentence) should be shown within the working space. For example, written information is presented in short sentences instead of a long sentence.	The whole image or sentence will enhance a user's understanding.	4.1 (0.74)	4.1 (0.57)
		A user does not want to enlarge all components in the 3D virtual space but a specific components (or area).	An e-magnifier (partial enlargement) with a color enhancement function should be available.	A user can carefully observe a given environment.	3.9 (0.88)	4.0 (0.47)

Vision-related individual-difference study (low vision group versus sighted group)

Category	Sub-category	Condition	User needs	Description	Degree of agreement	
					Low vision	Sighted
Audition	Speech	A user would like to be briefly informed of the whole structure of UIs before performing any activity.	A user should be verbally informed of the overall structure of information on screen (such as the locations or the number of virtual objects) line-by-line.	Building a mental image of user interfaces (UIs) in the 3D virtual space will contribute to a user's space perception.	4.4 (0.52)	3.8 (1.32)
		A user tries to understand a virtual widget by touch. However, the user is not good at handling a virtual pointer.	Speech sound (human voice) should describe the features (shape, size, function, etc.) of a virtual widget when a user's virtual pointer touches the widget.	Due to a user's visual impairment, other modalities can be used. Auditory feedback contributes to a user's understanding.	4.2 (1.03)	3.8 (1.40)
		A user tries to understand a virtual widget by touch. However, the user is not good at handling a virtual pointer.	If speech sound is used, natural human voice should be implemented instead of synthetic voice.	A synthetic voice is not user-friendly.	3.9 (0.99)	4.0 (0.82)
		A user gets lost while navigating or finding certain widgets in the 3D virtual space.	A user should be verbally informed of the current location upon a user's request.	Due to a user's visual impairment, other modalities can be used. Auditory feedback contributes to a user's understanding.	4.4 (0.52)	4.2 (0.42)
		A user needs to trigger an event. However, the user does not want to rely on either a sense of vision or touch.	A voice-command function should be available.	In addition to visual impairments, a user could possibly have Carpal Tunnel Syndrome, which results in abnormality of touch sensitivity. Such a user needs auditory clues to interact with the system.	4.0 (1.05)	4.3 (0.48)
	Non-speech	Besides menus on a menu bar, a virtual button can also be embedded inside the 3D virtual space. For example, if a user pushes a virtual button down, the user should be sure the button has been fully pushed down to trigger an event.	When the virtual button is pushed down, a user should hear a non-speech sound (such as a click) as feedback.	Additional clues contribute to a user's ease of understanding.	3.7 (1.34)	3.7 (1.25)
		The user's virtual pointer is approaching the boundary of a 3D virtual space. Afterward, the pointer touches it.	A user should be informed of the virtual boundary via the combination of vibration and speech sound. An alert should occur before touching the boundary instead of at the time of touching it.	Timing is critical: a user does not want to wait until the user's virtual pointer hits the boundary. A combination of two different sensory modalities (force feedback and auditory feedback) can increase a user's chances of understanding a situation.	3.7 (1.25)	3.3 (1.16)
Touch	Accuracy	A user gets lost in the virtual space while navigating or finding certain objects. The user does not know where a reference point is located in relation to the user's current position. The user decides to ask a system for help in order to return to a reference point or a pointer's previous position.	A virtual pointer should guide a user.	The automatic guidance can reduce a user's cognition workload.	4.5 (0.53)	3.8 (0.63)
		A user loses contact with a virtual widget	A virtual pointer should guide a user to	The automatic guidance keeps a user	3.9	3.4

	while following its contour.	follow the contour of a 3D virtual widget upon a user's request.	from losing contact.	(0.88)	(0.97)
	A user loses contact with a virtual widget while following its contour.	A user should be given a means of returning to the starting position.	The guidance will save a user's time and effort.	3.9 (0.88)	3.9 (0.57)
	A reference point is located differently over subpages.	A reference point should be located at the same place through all subpages. A system should provide consistency in user interfaces through the whole system.	A reference point serves as a “lighthouse” for a user in the 3D virtual space. It should not be changed, thereby helping a user have better space perception.	4.2 (0.79)	3.9 (0.57)
	A user chooses to rely on a programmed movement of the virtual pointer that guides a user toward a certain widget. When the user's virtual pointer touches a widget, he or she realizes that the widget is not what the user wanted.	A user should be guided to return to a reference point.	A user can save time and effort through the system's guidance.	3.9 (1.37)	4.2 (0.63)
	A user needs to adopt a system and spend time getting familiar with the position of a reference point.	A user should be allowed to assign a certain position to a reference point based on the user's preference.	A user usually assigns a certain place to a reference point that is the most convenient place to detect. A user will be more likely to find it without a mistake.	4.5 (0.71)	4.3 (0.48)
Force bandwidth	When a user touches a virtual button, a user would like to receive confirmation.	When a user touches a virtual widget, force-feedback (vibration) should be generated.	A system should always keep users informed about what is happening through appropriate feedback within a reasonable time.	3.7 (1.06)	4.1 (0.88)
	A user's virtual pointer moves around to get the overview of the 3D virtual space.	A user should experience haptic feedback (such as vibration or throbbing) when a user's virtual pointer is hovering over objects in the virtual space; this feedback is performed upon a user's request.	A novice user is not good at operating the system and exploring the virtual space. Additional methods of feedback can enhance the user's operation.	4.3 (0.67)	3.7 (0.95)
	A user moves the pointer across a thin gap between two virtual buttons, but the user fails to recognize the gap. Consequently, the two buttons are recognized as just a single button.	A magnetic force should be placed between two virtual widgets (such as buttons). Therefore, a user would feel strong detent force when the virtual pointer moves across the two widgets.	A detent force serves as a clue for a user to distinguish between a button and gap.	3.5 (1.35)	4.0 (1.05)
Sensing acuteness	A user loses contact with a virtual widget while following its contour.	A user should be given a 2D widget instead of a 3D widget.	A 2D widget helps a user understand its figure efficiently because a 3D widget has a greater potential for loss of contact.	2.4 (0.70)	2.9 (1.10)
	A user loses contact with a virtual widget while following its contour.	A user prefers a raised line on the edge of a virtual widget rather than a grooved line on the edge.	A raised line on the edge is more distinctive than a grooved line for a user with visual impairment. Thus, a user can avoid losing contact.	3.9 (0.99)	2.9 (0.99)
	A user loses contact with a virtual widget while following its contour.	A virtual widget with a raised line is more efficient than a widget with texture in terms of acute sense.	A raised line on the edge is more distinctive than texture for a user with low vision. A user can avoid losing contact.	3.2 (1.14)	3.2 (0.92)
	A user is likely to be confused as to the degree to which a slider type (or clock type) of button is moved.	A push type of button should be used in the 3D virtual space because it is the most preferred design compared to others (such as a switch up-down button	A push button is the easiest type for a user to understand in terms of its movement and the degree to which a status is changed. A push button shows	3.9 (0.88)	3.4 (0.97)

		and a clock type button).	only two statuses: on and off, making it is easier for a user to perceive changes.		
	Besides a main console (such as a menu bar and toolbar), a virtual button is often embedded in the 3D virtual space. Such a user interface element provides a user a simple way to trigger an event. A user gets a button switched from 'on' to 'off' or vice versa. If a push button is not designed to remain down for an 'off' status, there is a possibility of a user considering the button to be an 'on' button.	When a push button is switched from 'on' to 'off' or vise versa, different textures should be assigned to the button.	In graphical user interfaces (GUIs), activating a button makes its associated content visible and the button itself usually becomes highlighted with different colors to distinguish it from other inactive ones. In haptic user interfaces (HUIs), different textures can be used instead of different colors.	3.1 (1.20)	3.6 (1.17)
	How a button should be designed to identify disabled buttons/menus/taps that are not supposed to allow double clicks is a critical design issue because such a disabled button can still be used as a reference point for users with visual impairments.	After a push button is pushed down, the push button should immediately return to the original height.	Potential solutions might include making the disabled buttons remain touchable and visible, but also to assign different types of textures to the disabled buttons.	3.9 (0.74)	3.8 (1.03)
	A series of virtual widgets (such as button) are placed close to each other. A user misses the last one.	A virtual string should be presented between two virtual widgets (such as button). The string tells a user there is another virtual widget. Thus, a user does not miss the widget.	Even better than good error messages is a careful design that prevents such a problem from occurring in the first place. A designer should eliminate error-prone conditions.	4.0 (0.94)	4.2 (0.79)
	Multiple virtual buttons are placed close to each other.	Different textures should be assigned to two different virtual widgets (such as buttons) that are closely located.	Even better than good error messages is a careful design that prevents a problem from occurring in the first place. A designer should eliminate error-prone conditions.	4.1 (0.88)	3.6 (1.43)
	All virtual buttons share identical figures regardless of their functions.	Virtual buttons with different functions should have different figures (such as size and shape).	Additional clues contribute to a user's ease of understanding.	4.1 (0.88)	4.0 (1.43)
	Multiple virtual buttons are placed close to each other. While some are on the ground, the others are in the air.	Different textures should be assigned to the top and bottom of a virtual widget.	Even better than good error messages is a careful design that prevents a problem from occurring in the first place. A designer should eliminate error-prone conditions.	3.3 (0.95)	3.0 (1.41)
	Multiple virtual buttons are placed close to each other.	Instead of rough texture, soft texture should be assigned to the top of a widget.	A repeated lateral motion on a coarse texture will be likely to give a user an uncomfortable sensation. In addition, accumulation will make a sense of touch insensitive.	3.1 (1.20)	2.6 (1.51)
	Multiple virtual buttons are placed close to each other. A user needs to distinguish them.	Textures (e.g., sandpaper) should be assigned to the edge of a widget instead of the whole surface.	The edge is the first place a user with visual impairments will approach.	3.0 (0.94)	3.0 (1.33)
	In the real world, a user prefers square shaped widgets because they are easy for the user to find a certain one among	A square is the easiest shape to understand by touch.	Matching between the system and the real world will increase a user's satisfaction.	3.2 (1.32)	3.0 (1.41)

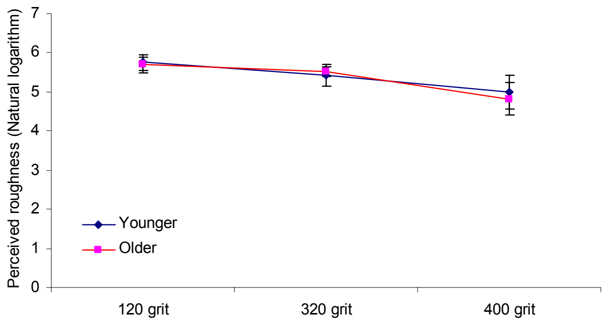
		others.				
		A user enters a virtual space full of widgets with various shapes.	A virtual widget with a complex shape should not be intentionally avoided in designing the 3D virtual space.	The real world contains a lot of complicated shapes.	3.4 (1.35)	3.8 (1.03)
	Velocity	A user gets lost while navigating or finding certain objects. The user does not know where a reference point is located from the user's current position. The user decides to ask the system for help in order to return to a reference point.	When a user's virtual pointer is guided by a system, different routes should be available for a user to choose from, based on duration and distance; for instance, a user can either quickly jump to the reference point or slowly follow the user's track back.	The choice of following the user's track back contributes to a user's space perception, and the choice of directly jumping contributes to saving the user's time.	4.2 (1.23)	3.4 (0.70)
		A user controls a system's input device (such as a mouse) that is associated with a 3D virtual pointer. It is not easy for a user to follow a fast move of a 3D virtual pointer on the screen.	A user should be allowed to adjust a 3D virtual pointer speed.	Adjusting the virtual pointer speed is a necessity for certain users. If a user wants to play a fast-paced application with a lot of dynamic movements, a faster pointer speed is desired. Sometimes a user plays with a delicate move,	4.5 (0.71)	4.3 (0.67)
	Workspace size	When users pick up a wrong widget, they limit themselves to moving around the wrong object and then expend a little bit of time and effort.	Virtual widgets should be arranged not too far each other.	Placing widgets close to each other will increase the possibility of being detected by a user with visual impairments.	3.6 (0.97)	2.9 (1.10)
		When a user interacts with a group of virtual widgets, the user typically tends to scan a working area by moving from left to right and vise versa instead of up and down.	Virtual widgets should be arranged on a horizontal line instead of a vertical or curvy line.	A user can successfully locate all objects by moving horizontally.	3.9 (1.20)	3.1 (0.57)
		The distance between each virtual button on the main page is 1 inch. A user gets used to the distance of 1 inch. However, the distance on subpages is 2 inches. When the user visits subpages, the user misses a virtual button.	Besides menus on a menu bar, a virtual button can be embedded inside the 3D virtual space. Space between two virtual buttons should be consistent throughout the whole system.	Users should not have to wonder whether different words, situations, or actions mean the same thing.	4.0 (1.05)	3.8 (1.03)
		All virtual buttons are randomly placed regardless of their features (such as size, shape, and function). A user gets confused. Even a returning user must put considerable effort into recall.	Virtual buttons should be grouped and placed separately by considering their features (such as size, shape, and function).	Systemically arranged buttons contribute to a user's ease of understanding.	3.9 (1.20)	3.9 (0.74)
		The user's virtual pointer is approaching the boundary of a 3D virtual space.	When a user attempts to reach over the boundary of the 3D virtual space, the boundary should be noticeable by locking a user's virtual probe.	A novice user is not good at operating the system and exploring the virtual space. Additional feedback will enhance the novice user's operation.	3.8 (1.14)	3.0 (1.05)
		A system is initiated, and a user just enters a virtual space.	Once a system is activated, it should provide a user with a chance to perceive the whole space size by guiding a user to touch and feel the space boundary in the following order: 1. the boundary of the space, 2. middle of the space, and	Recognizing the whole space size will enhance a user's space perception.	4.2 (0.63)	3.9 (0.88)

			3. everything else.			
vision	Icons	A 3D virtual space contains various content, such as a reference point and other virtual widgets. A user gets confused and spends a lot of time locating a certain widget in the 3D virtual space.	A reference point should be designed to be distinctive from other widgets in the 3D virtual space by assigning a light-emitting diode (LED) type of light to the reference point.	A reference point serves as a “lighthouse” for a user in the 3D virtual space.	3.2 (1.03)	3.8 (0.63)
		All widgets in the 3D virtual space have the same color.	Different colors should be used to distinguish between virtual widgets that share identical figures (size and shape).	A user with low vision needs additional clues to understand the world.	3.5 (1.18)	3.7 (0.82)
		The clarity of contents presented in the 3D virtual space generally has an influence on a user's ease of viewing and reduced eyestrain.	The color of user interfaces should be changeable to black and white, yellow on black, and inverted brightness.	Color enhancements improve clarity of content in the 3D virtual space by providing easier viewing and reduced eyestrain.	4.3 (0.95)	3.8 (0.82)
		A user with residual vision (or low vision) enters a virtual space that is full of virtual widgets. The user would like to get the “big picture” through the sense of vision.	All widgets in the 3D virtual space are seen through a virtual screen cover. The cover enables a user to see only a certain portion of the whole virtual space. Thus, the rest is blocked with a screen cover. A user should be able to see all objects at once instead of one-by-one in a series.	Typically, an individual with low vision prefers to see all when he or she enters a room. Seeing all at once will contribute to a user's space perception. If there is a certain thing the user becomes interested in, the user can carefully observe the area.	3.3 (0.52)	3.4 (0.63)
		A group of widgets are located close to each other. They look similar.	If the same color should be applied to widgets that are located close to each other, different marks such as striped line should be used to make them distinctive.	A user with low vision still relies on vision. Color is still important.	4.2 (1.03)	3.8 (0.92)
		A user tries to understand a widget by touch (e.g., enclosure).	The size of a virtual widget should be similar to the size of a palm.	If an object is too big, it is also easy to fail to understand its shape.	3.4 (1.07)	3.2 (1.32)
	Menus	A user chooses to rely on a programmed movement of the virtual pointer that guides a user toward a certain virtual widget. When the user moves a virtual pointer to the widget. he or she realizes that the widget is not what the user wanted.	A user should be given a confirmation message that asks whether the user wants to stay or leave (e.g., going back to the reference point or previous point). No activity should be allowed until the confirmation message is cleared.	The dialog box provides a user control to specify how to carry out an action. It contributes to a user's error prevention.	4.0 (1.15)	3.8 (0.92)
		A user spends a lot of time understanding menus, interfering with a user's primary task.	A user should be given a small number of virtual buttons (or menus).	Minimal designs reduce a user's cognitive workload.	4.4 (0.52)	4.2 (0.63)
		A user often makes mistakes in computing; for example, a user ends up clicking "OK" on the dialog; "Are you sure you would like to quit the program without saving?" A user does not pay	A reset or undo button should be available. A user should be able to escape from an unwanted status by using a reset or undo menu. The reset or undo menu lets a user start from the	By hitting a reset or redo button, a user can work his or her way back to a point before the mistake was made. As a result, a user’s feeling of being in control will increase.	4.5 (0.85)	4.3 (0.67)

		attention to the dialog because he or she clicks “OK” too often.	beginning.			
		A user is not good at computing and feels uncomfortable with a written manual.	A novice user should be able to take a demonstration or orientation session.	A user can quickly adopt and learn how the system works through a walk-through session.	4.6 (0.52)	4.6 (0.52)
	Pointers					
		A user loses contact with a widget.	A user should be visually informed of how far a user's virtual pointer is away from the target object; for example, a system presents a line from the target widget to the virtual pointer.	A visual cue will be helpful because the user is still able to rely on a sense of vision.	4.0 (1.05)	3.4 (1.17)
		A user should trigger an event.	A shortcut key on a keyboard should be compatible with a right click on a mouse (or stylus).	A user can trigger the same event by using either a shortcut key or a right click. A user should have a choice.	3.7 (1.34)	4.1 (0.99)
	Windows	A user does not want to enlarge all components in the 3D virtual space but specific components (or areas).	An e-magnifier (partial enlargement) with the color enhancement function should be available.	A user can carefully observe a given environment.	3.9 (0.88)	4.0 (0.94)

APPENDIX E: Graphs of data analysis results (no significant)

- The AGE x SANDPAPER interaction



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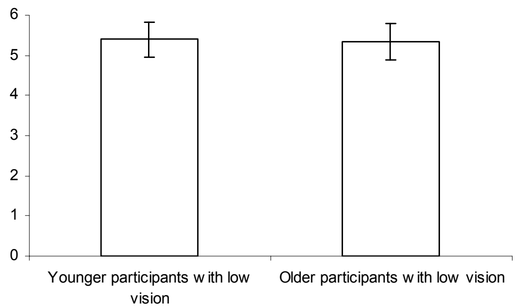

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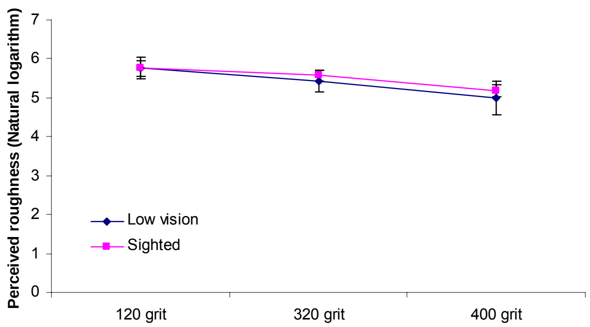

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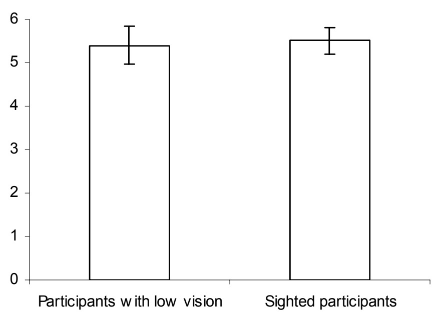

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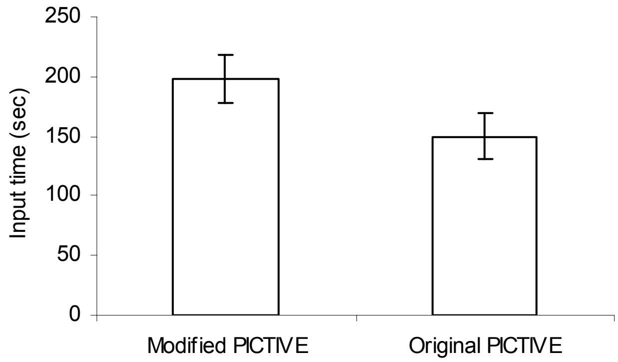

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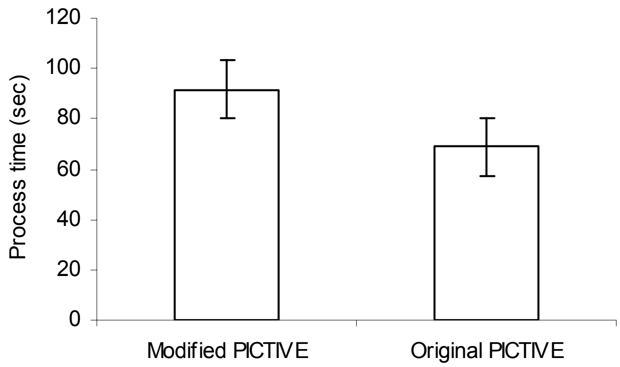

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DATE: February 17, 2010

MEMORANDUM

TO: Tonya L. Smith-Jackson
Hyung Nam Kim
Heidi Kleiner

FROM: David M. Moore

Approval date: 3/16/2010
Continuing Review Due Date: 3/1/2011
Expiration Date: 3/15/2011

SUBJECT: **IRB Expedited Continuation 1:** "Usable Accessibility and Haptic User Interface Design Approach" , IRB # 09-217

This memo is regarding the above referenced protocol which was previously granted expedited approval by the IRB. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. Pursuant to your request, as Chair of the Virginia Tech Institutional Review Board, I have granted approval for extension of the study for a period of 12 months, effective as of March 16, 2010.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtain re-approval from the IRB before the study's expiration date.
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