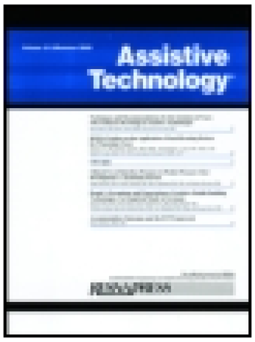

Assistive Technology

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A Review of Principles in Design and Usability Testing of Tactile Technology for Individuals with Visual Impairments

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The quality and quantity of assistive technologies available for individuals with visual impairments have grown substantially as computers have become more available and increasingly complex hardware platforms have entered the market. The concept of sensory substitution for individuals with visual impairments was initially discussed by Bach-y-Rita et al. in a seminal study showing that the adult brain has sufficient neuroplasticity to substitute tactile stimuli for visual information (1969). The first mainstream sensory substitution devices, such as the Optacon and Tactile Vision Substitution System, were based on an array of pins that could be raised and lowered to create refreshable images (Bach-Y-Rita & Hughes, 1985). When text-to-speech software improved, audio became another mode of conveying information. As technology has developed in other fields, including human-computer interaction, devices that are able to provide increasingly precise and responsive tactile feedback, often called haptics, have also become available (Kahol, Tripathi, & Panchanathan, 2005). More recently, haptic feedback, virtual environments, and multimodal adaptations have been on the rise, with focus on making mainstream technology such as touch screens accessible for those with visual impairments (Kane, 2011; Yao & Leung, 2012). As new devices are designed and tested, it is important to evaluate these experiences to determine what platforms have been used most successfully, what design principles have been found to be the most effective, and what strategies can be used to include individuals with visual impairments in the process.

Significant progress has been made in terms of product reliability and effectiveness of assistive devices. Research on haptic perception and multimodality has significantly contributed to a broader understanding of how non-visual sensory information is perceived (Klatzky & Lederman, 2003). Haptic perception integrates signals from the skin receptors and proprioceptors to allow for object and pattern identification and recognition (Rincon-Gonzalez, Naufel, Santos, & Helms Tillery, 2012). Those who are blind rely particularly on haptic perception to process external stimuli and spatial information. Research has shown that individuals with congenital blindness experience enhanced vibrotactile perception (Wan, Wood, Reutens, & Wilson, 2010) and spatial resolution, and that individuals who are blind are less likely to experience an age-related decline in tactile acuity than their sighted counterparts

(Legge, 2008). This is useful in conveying spatial information, as research has also shown that even individuals with congenital blindness have a fully-developed ability to understand spatial information from tactile input (Tinti, Adenzato, Tamietto, & Cornoldi, 2006; Guidice, Betty, & Loomis, 2011). In addition to having enhanced sensory perception, research by Withagen et al. suggests that children who are blind tend to have better short-term memory and verbal working memory, which play a role in auditory and tactile processing, than their sighted counterparts (2013). Therefore, assistive devices commonly provide multiple modes of feedback, such as touch and sound, to convey information (Yu, Kangas, & Brewster, 2003). This is supported by more general research on multimodality, which has shown that it is often most effective to communicate information through more than one sensory channel (Turk, 2014).

The incorporation of a user testing process, in which individuals from the intended user population test the device and give feedback about its ability to meet their needs, is an essential element of the design process. Over time, the principles of iterative user-centered design have been increasingly emphasized as best practices in the field of user testing, and are used to ensure the accessibility of software and devices (Petrie & Benev, 2009). Iterative user-centered design requires that user feedback be included throughout the entirety of the design process, from identifying user needs to prototyping and final testing. The goal of this approach is to design devices that more closely fit the needs of the intended user population (Nielsen & Landauer, 1993). While user testing can be a challenge in device development for smaller target audiences, such as individuals with visual impairments, many of the studies included in this review successfully incorporate extensive user testing into the device design process (Ashcroft, 1983; Tzovaras, Nikolakis, Fergais, Malasiotis, & Stavrakis, 2004; Ando, Tsukahara, Seki, & Fujie, 2012).

This systematic literature review has three distinct aims: 1) to determine how the technologies available have historically contributed to research on assistive devices, in order to depict a landscape of hardware platforms used in the development of assistive devices; 2) to categorize and discuss the main accessibility issues addressed by researchers while developing assistive devices; and 3) to systematically examine the methodologies previously adopted to test the usability of assistive devices.

Methods

Data sources

A systematic review was conducted to identify the available findings and evidence on assistive technology for individuals with visual impairments in a methodical and replicable manner (Torgerson, 2003). Articles were identified within several databases in the EBSCO suite covering academic literature on technology, disability, and education. The databases included were Academic Search Premiere, the Psychology and Behavioral Sciences Collection, Education Research Complete, Business Source Complete, Computers & Applied Sciences Complete, and the Education Resources Information Center.

A combination of search terms was used to locate articles published between 1980 and 2014 that mentioned terms related to visual impairment (blind OR "visually impaired" OR "visual impairment*"), technology (device OR technology OR interface), and sensory adaptation (haptic OR tactile OR multimodal) within the title or abstract. Results were filtered to only include articles classified as Academic Journals, Reports, Trade Publications, or Conference Proceedings. Duplicate citations were removed in cases where the same article was indexed in multiple databases.

Inclusion/Exclusion Criteria

From the initial set of articles that matched these search terms, relevant articles were identified from an initial screening of the title/abstract alone followed by an in-depth review of the full text of the remaining articles.

Articles included in the final review met all of the following criteria:

1. Article addresses the development of a personal, electronic, assistive device with a tactile component.

2. Technology is developed specifically for users who have some form of visual impairment.

3. Article describes the original development or testing of a specific device.

4. Article includes the results of testing by at least one user who is blind or visually impaired.

Articles were excluded from the review if they met any of the following criteria:

1. Article is a review of studies on multiple devices and does not include a sufficiently detailed description of a single device.

2. Article describes a system that has no electronic or computational component (e.g. papers describing swell paper or tactile models alone) or no tactile component (e.g. devices with only an auditory output).

3. Article does not mention testing the device with users.

4. Article mentions testing the device with sighted users, but does not indicate testing with at least one user who is blind or visually impaired.

5. Article describes the design of a device implemented in a public space (e.g. crosswalks or signs) and not the development of a personal device.

6. Article describes a device designed solely to collect data in a research setting, and not to act as an assistive device to the user.

In order to gain a broad view of the types of technology available, this review was not limited to devices used for a specific type of application (e.g. reading, navigation, or learning). However, it was limited to personal, electronic devices because the issues faced in designing public assistive technologies and accessible public spaces are distinct from those faced in designing personal devices. Devices that did not include at least some tactile component were also excluded. To specifically identify research on devices that have been used by the visually impaired community or could be used in the future, the studies reviewed were limited to those that had conducted at least some level of user testing. It was required that the devices were tested by at least one person with a visual impairment, as opposed to only sighted users, because it is well documented that there are significant differences in how people with and without visual impairments perceive information and interact with devices (Bach-Y-Rita & Kercel, 2003).

To focus on relatively current research, the search was limited to articles published after 1980 because the quantity of research published on assistive devices for individuals with visual impairments substantially increased in the early 1980s (Smith & Kelly, 2014). General review articles that did not include specific information about individual devices, but may have provided a broader or more complete analysis of device development, were excluded.

The initial search yielded 300 results, excluding duplicate listings between databases. Of these articles, 62 were determined to be relevant after a first pass title/abstract review followed by a second pass reading of the full text of remaining articles (see Table 1). All decisions were cross-checked by a minimum of two reviewers to ensure consistency in the application of the inclusion/exclusion criteria. Most articles excluded in the first pass were either not about the topic of visual impairment or did not describe a specific personal, assistive device. Most articles excluded during the full text review were excluded because the study did not mention usability testing with at least one user who is blind or visually impaired.

[Insert Table 1 here]

Data Extraction

From each included article the following information was collected in a standardized matrix: title, author, year of publication, number of users who tested the device (stratified by level of visual impairment, age, and gender of participants where possible), hardware platform mode of user interaction (e.g. tactile and/or auditory), significant results of device development and/or testing, and intended application of the technology (e.g. navigation, education, etc.). The information collected in this matrix was then used to synthesize the data into summary tables for each specific aim, indicating patterns in user testing, choice of hardware platform, and application area among devices.

Results

Hardware Platforms

The availability of increasingly complex, responsive, and adaptable hardware platforms has driven improvements in assistive technologies for individuals with visual impairments. The first specific aim of this review is to identify which hardware platforms were the most widely used and served as a basis for the development of effective assistive devices. In order to gain a broad view of the progression of device development, papers were first categorized by the hardware platform they used for device development (see Table 2). Most systems were based on one of three basic hardware categories:

1. Pin matrices, which are tactile displays built from an array of small pins that can be individually raised or lowered to create an image, similar to braille. Pin matrices permit users more than one point of contact and provide representations that most resemble real world counterparts. However, pin matrices are limited in resolution due to the spacing of the pins; likewise, their high cost make them relatively unavailable to most blind persons (O'Modhrain, Giudice, Gardner, & Legge, 2015).

2. Force feedback systems, which generate a force on the user's finger or hand as it moves to communicate spatial information. Many of these systems are restricted to a single point of

contact and provide more abstract tactile information that the user must learn to interpret. Benefits include rapid rendering, three dimensional renditions, and presentation of both static and dynamic effects (O'Modhrain et al., 2015).

3. Tablets and touch screens, which combine vibration and/or auditory feedback with standard visual displays. Currently, many touch screens are limited by their resolution, single point of contact, and the inability to provide stimulus when the user's finger is not in motion on the screen. They are promising in that they are quickly refreshable and less expensive than pin matrices (O'Modhrain et al., 2015).

People with visual impairments have used all three types of devices successfully, and each has its advantages in communicating information quickly and efficiently. The hardware components of the devices reviewed varied widely in complexity. While some devices included complex tactile systems, others were based almost exclusively on interaction with a standard interface such as a computer. Recently, several devices have been developed using vibration and auditory feedback from standard touch screens and tablet devices to make graphical material accessible (Giudice, Palani, Brenner, & Kramer, 2012; Poppinga, Magnusson, Pielot, & Rasmuss-Grohn, 2011). New technology has entered the market that allows for the development of touch screens that provide tactile feedback to the user through electrostatic interaction. This may allow future development of assistive technologies for applications in which the use of a tactile touch screen is extremely practical (Kim, Israr & Poupyrev, 2013).

Many of the reviewed papers discussed custom-built devices, most still in the prototyping phase, designed for a fairly specific application or population of users. These devices included tactile displays, computer interfaces, force feedback canes, tactile stimulators for various parts of the body, and virtual reality systems (Velasquez, Bazan, Varona, Delgado-Mata, & Gutierrez, 2012; Zelek, Bromley, Asmar, & Thompson, 2003; Tzovaras et al., 2004). A few commercially available devices, however, have been studied extensively for a broad variety of accessibility needs. One of the first pin-matrix devices was the Optacon, a pen-shaped device with a camera on one end that translated images to a small pin matrix on the other. This was used in a variety of ways, from reading text to viewing images, and was the precursor to even larger and more complex pin matrix displays (Bach-Y-Rita & Hughes, 1985). The most widely studied force-feedback device in this review is the Phantom, a device that applies varying forces to the user's finger as they move it around to simulate contact with objects in a virtual environment (Sjostrom & Rassmus-Grohn, 1999). A more recent commercially available technology is the Talking Tactile Tablet, a tablet that can have swell paper images attached on its surface and plays programmed auditory feedback when the user touches certain areas of the picture. This has been applied especially well in educational and assessment environments (Hansen, Shute, & Landau, 2010; Landau, Russel, & Erin, 2006; Rovira & Gapenne, 2009).

The devices that have successfully been made commercially available have several characteristics in common: they are simple and flexible enough to be adapted for a variety of applications, they communicate information to the user in an interactive way, and they can be combined with auditory feedback or other types of input to create a multimodal environment for the user. While the optimal design parameters for each device vary widely based on the application it is intended for, as well as the needs of the individual user, many of the articles reviewed emphasized the advantages of these overarching design principles.

Applications of Assistive Devices

The second specific aim of this review is to identify the intended applications for these assistive devices in order to determine which specific needs of the visually impaired community are being addressed by current research. After categorizing articles based on application (see Table 3), it was found that the most common applications of assistive technologies for individuals with visual impairments are navigation, education, and computer accessibility. These have been consistently identified as areas where assistive technology can benefit individuals with visual impairments. However, there is still much room for improvement in the technology available to address each of these challenges, and therefore they should remain important themes for future research.

Twenty-six studies, over a third of the reviewed articles, intended to teach or improve learning for students who are visually impaired. Of these, 12 covered STEM topics, from mathematical graphs (Gorlewicz, Burgner, Withrow, & Webster, 2014) to model-based astronomy and geology (Saarinen et al., 2006) to information technology (Armstrong & Murray, 2010). As the overall need for STEM education has increased, there is an increasing emphasis on research in this field, as all 12 of these studies were published after 2000. Another nine studies focused on more general educational needs such as data visualization (Paneels, Ritsos, Rodgers, & Roberts, 2013) and spatial cognition (Miletic, 1994). Three focused on teaching writing and drawing, while another three focused on occupational skills such as identifying common objects (Chit & Yap, 2012) and using ATM machines (Wake, Wake, & Takahashi, 1999).

Several educational studies successfully created virtual reality environments for object exploration, emphasizing the benefits of providing guided exploration (Saarinen et al., 2006; Tuominen et al., 2008), reference points (Saarinen et al., 2006), and clear boundaries (Bernareggi, Mussio, & Parasiliti Provenza, 2009; Jones et al., 2014) to orient students in the virtual reality environment. Many studies demonstrated the benefits of providing multimodal output (Plimmer, Reid, Blagojevic, Crossan, & Brewster, 2011; Nam, Li, Yamaguchi, & Smith-Jackson, 2012; Gorlewicz et al., 2014), particularly using synthesized speech to provide additional context or feedback to the student (Sjostrom, Danielsson, Magnusson, & Rassmus-Grohn, 2003; Tuominen, Kangassalo, Hietala, Raisamo, & Peltola, 2008; Hansen, Shute, & Landau, 2010). The effectiveness of haptic, multimodal technology for learning has been confirmed through educational and cognitive research (Sankey, Birch & Gardiner, 2010).

The next largest application was navigational aid, addressed by 19 of the studies examined. As the technology available for assistive devices has improved, it has greatly expanded the possible platforms for navigational aids, and all 19 of the studies in this review addressing navigation were published after 2000. The prevalence of research in this area reiterates the importance of daily navigation for those who are visually impaired. Ten of these studies investigated navigation through physical environments and obstacles by providing information such as accessible maps (Wang, Li, & Li, 2012; Moustakas, Nikolakis, Kostopoulos, Tzovaras, & Strintzis, 2007), real-time directions based on the user's location (Marston, Loomis, Klatzky, & Golledge, 2007), and feedback about the surrounding area (Zelek et al., 2003). The majority of these articles showed that haptic feedback is particularly useful for aiding in obstacle avoidance

(Hill & Black, 2003; Zelek et al., 2003; Simpson et al., 2005; Ghiani, Leporini, & Paterno, 2009).

The remaining eight navigation studies created and explored virtual reality representations of physical environments. Research has shown that users can successfully transfer spatial information from virtual environments to physical environments, and that users trained in in virtual environments can perform comparably in navigation tasks to those trained in physical environments (Merabet, Connors, Halko, & Sanchez, 2012). Many virtual reality devices simulate the feedback provided by a cane, as the cane is a familiar explorational tool for many individuals with visual impairments (Tzovaras et al., 2004; Magnusson & Rassmus-Grohn, 2005; Tzovaras, Moustakas, Nikolakis, & Strintzis, 2009; Ando et al., 2012). Studies suggested that there was significant variability in users' exploration strategies (Lahav & Mioduser, 2004; Tzovaras et al., 2009; Lahav, Schloerb, & Srinivasan, 2013), thus emphasizing the need for navigational environments to be adaptable to these different strategies.

Computer accessibility has also been a growing field for device development. Computer accessibility was the focus of 10 of the reviewed articles, eight of which were published after 2000. Three studies used computer games to test their devices, reflecting a growing trend of gamification in research (Deterding, O'Hara, Sicart, Dixon, & Nacke, 2011). Seven studies focused on computer navigation such as menu selection for Graphical User Interfaces (Edwards et al., 2005; Jacko et al., 2005) and web navigation, representation, and display (Yu, Kuber, Murphy, & McAllister, 2006). Research shows that by adding vibrotactile and/or auditory feedback, standard touchscreens can be successfully adapted for use by individuals with visual impairments (Kane, 2011; Gorlewicz et al., 2014). The need for research focusing on touch screen and computer accessibility will continue to increase as a result of computers becoming more commonplace in everyday use and central to society.

The need to address challenges in education, navigation, and computer accessibility remains relevant today, and recent research continues to focus on all of these problems. As accessibility research moves forward, it must address the needs of device users as reflected by these past research trends, while adapting to new needs that arise as technology continues to change.

Usability Testing

The final specific aim of this review is to comprehensively analyze usability testing, which offers valuable data in terms of examining past efforts and structuring future studies. Ideally, studies are able to include a representative group from the population intended to use the device. The fact that 52 articles were excluded in the full text review simply due to lack of user testing by participants with visual impairments indicates that a significant portion of current research is unable to do this. This is partially due to the difficulty that many researchers experience recruiting visually impaired users to validate technology. In the studies including usability testing by blind and visually impaired users, most of the participants were recruited either through word of mouth, from personal connections, or by contacting regional organizations for blind and visually impaired persons. It is essential that usability testing by users with visual impairments is made a priority, as no device can be effectively validated if it is not tested by individuals in the target user audience.

The number of users required for a study can vary widely, whether the intent is to test usability or statistical significance. It is generally accepted that a sample of five to ten users is sufficient for usability testing, and it is estimated that five users are able to find an average of 85% of usability issues (Nielsen & Landauer, 1993; Faulkner, 2003). Alternatively, in studies that require statistically significant results in addition to usability feedback, the number of users required to achieve significant results varies between 11 and upwards of 2,000 users, based on a number of different variables (Cohen, 1992). These larger sample sizes can be difficult to recruit due to the relatively small proportion of people with visual impairments in the general population. However, data from 20 users may be sufficient for significance in many situations (Nielsen, 2006). Table 4 shows the distribution of the number of participants with visual impairments included in each study. In studies that included more than one experiment, the experiment that included the largest number of users with visual impairments was counted.

In addition to testing with users with visual impairments, 19 of the 62 studies also included testing with sighted users, often blindfolded so that performance could be measured without interference from visual stimuli. Some of these studies purposefully included sighted users as test subjects because the device was intended for use by both visually impaired and sighted populations (Watanabe & Kobayashi, 2002; Kahol & Panchanathan, 2008). Other studies included sighted users as a pilot group to formalize the protocol and identify preliminary usability issues before recruiting users with visual impairments (Wake, Wake, & Takahashi, 1999; Brewster, 2002). Finally, some studies included sighted users as a control group for comparison to the performance of users with visual impairments (Edwards et al., 2005; Quek & Oliveira, 2013). Each of these techniques was used effectively in several of the studies reviewed. However, some other studies mentioned conducting testing with sighted users, but did not specify how this added to the data collected or improved the protocol for the study. Sighted users are not an effective substitute for blind users, as blind and sighted users perceive sensory input differently (Bach-Y-Rita & Kercel, 2003). Therefore, it is only necessary to include sighted users in the protocol if they serve a specific purpose, such as a pilot group or a control group.

Discussion

This systematic literature review aimed to determine which hardware platforms are often used for assistive technologies, to identify prevalent applications of assistive platforms, and to investigate the nature of user studies conducted with assistive technologies for blind individuals. The devices included in this review were limited to those listed in the EBSCO databases and tested with at least one visually impaired user. Of the 300 articles originally identified, 62 were determined to meet the criteria to be included in the review.

From these studies it was observed that, as the quality and quantity of available hardware has increased, the general variety and effectiveness of devices has increased accordingly. While older studies tended to use single-mode technologies, there is a growing trend in studies that incorporate devices able to provide multiple modes of feedback, which can be especially useful for individuals with visual impairments.

Although the hardware platforms in assistive technology are rapidly changing, the main applications of education, navigation, and computer accessibility have largely remained core issues for individuals who are visually impaired. In recent years, with the rise of assistive software, a larger emphasis has been placed on computer accessibility for visually impaired users, underscoring the need for them to interact and learn digitally.

While much progress has been made, many designs are not fully validated and tested by the intended user audience. Studies should include at least five users in order to collect qualitative data on a sufficient portion of usability issues, and more if statistical analysis on quantitative data is required (Nielsen & Landauer, 1993). While sighted users are not needed in all circumstances, they can be effectively used as a pilot group, a control group, or a secondary target audience, depending on the device.

Future research and development should intentionally focus on exploring promising hardware platforms and addressing the largest areas of need in the visually impaired community. It is expected that future technological developments will allow assistive devices to include increasingly responsive interfaces, capable of providing feedback to the user through multiple modalities.

In Table 5, recommendations for optimal device characteristics and general suggestions for structuring the design methodology of user studies are prescribed.

Developments in assistive technology also offer numerous benefits to individuals without visual impairments, as they can offer feedback through multiple modes and provide innovative strategies for all people to access complex sources of information more efficiently and effectively. As educational technology plays a prominent role in the classroom, and computer accessibility becomes an increasingly universal necessity, these application areas will be the most important to address. Finally, design should be centered upon users' needs, and developers should make it a priority to validate all devices with sufficient feedback from users with visual impairments. User-centered design processes, which include feedback from users in each step of the design process, should be used whenever possible.

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Table 1 Flow of articles through selection process

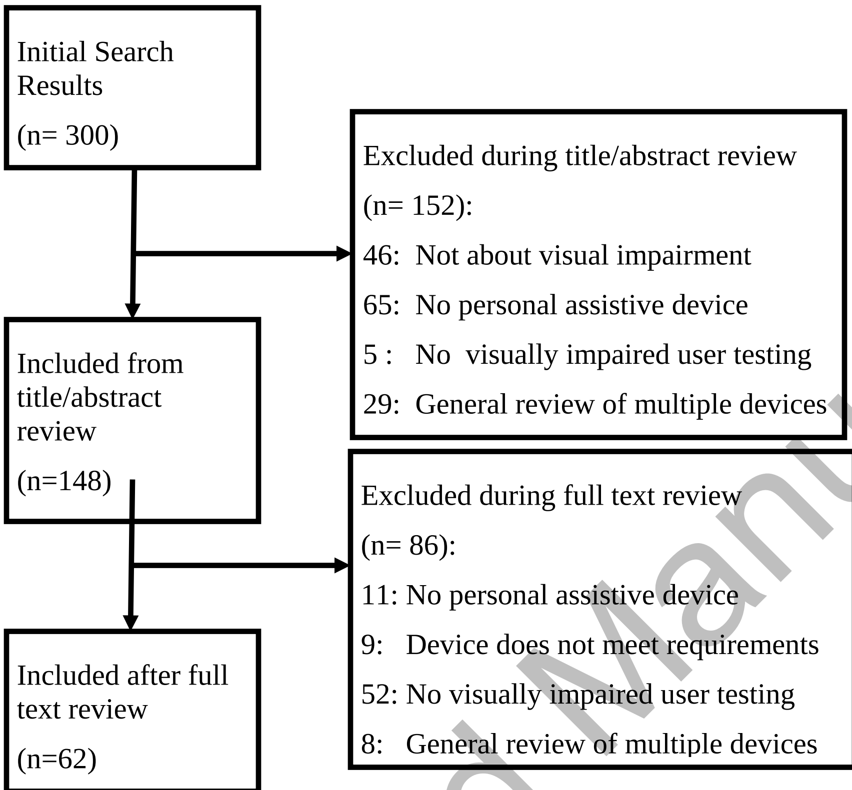

Table 2 Classification of hardware platforms

Device Type	Device Description	References
Pin Matrix	Optacon	Bach-Y-Rita & Hughes, 1985; Miletic, 1994; Miletic, Hughes, & Bach-Y-Rita, 1988
	Braille Cells	Rastogi & Pawluk, 2013; Rastogi, Pawluk, & Ketchum, 2013; Al-Qudah et al., 2014
	Pin Board	Guha & Anand, 1992; Ebina et al., 1999; Kurze, 1999; Kawai & Tomita, 2000; Watanabe & Kobayashi, 2002
Force Feedback	Haptic Glove	Zelek et al., 2003; Tzovaras et al., 2004; Kahol & Panchanathan, 2008; Bargerhuff et al., 2010; Quek & Oliveira, 2013
	Phantom	Sjostrom & Rassmus-Grohn, 1999; Brewster, 2002; Sjostrom et al., 2003; Bernareggi, Mussio, & Parasiliti Provenza, 2009; Magnusson & Rassmus-

	Grohn, 2005; Saarinen et al., 2006; Jones et al., 2006; Moustakas et al., 2007; Tuominen et al., 2008; Lahav et al., 2011; Plimmer et al., 2011; Chit & Yap, 2012; Kaklanis, Votis, & Tzovaras, 2013; Lahav, Schloerb, & Srinivasan, 2013; Paneels et al., 2013; Simmonett & Ryall, 2013
Body Site Specific (other than hands)	Simpson et al., 2005; Marston et al., 2007; Williams et al., 2011; Velazquez et al., 2012
Handheld-Cane/Rod	Hill & Black, 2003; Zelek, 2005; Ceipidor et al., 2009; Tzovaras et al., 2009; Ando et al., 2012; Jones et al., 2014
Force Feedback Mouse	Edwards et al., 2005; Jacko et al., 2005; Yu et al., 2006; Thebpanya, 2010
Game Controller	Raisamo et al., 2007; Petridou et al., 2011; Nam et al. 2012

	Other	Lahav & Mioduser, 2004; Ghiani, Leporini & Paterno, 2009
Tablet/Touch Screen	Tactile Tablet	Landau et al., 2003; Landau, Russel, & Erin, 2006; Rovira & Gapenne, 2009; Hansen, Shute, & Landau, 2010; Wang, Li & Li, 2012
	Touch Screen	Kane, 2011; Gorlewicz et al., 2014
Other	Computer	Ashcroft, 1983; Locke & Mirenda, 1988; Wake, Wake & Takahashi, 1999; Armstrong & Murray, 2010

Table 3 Classification of device applications

Application Field	**Application Description**	**References**
Education	STEM Learning	Landau et al., 2003; Sjostrom et al., 2003; Jones et al., 2006; Saarinen et al.,2006; Tuominen et al., 2008; Rovira & Gapenne, 2009; Armstrong & Murray, 2010; Hansen, Shute, & Landau, 2010; Nam et al. 2012; Quek & Oliveira, 2013; Jones et al., 2014; Gorlewicz et al., 2014
	Writing/Drawing	Watanabe & Kobayashi, 2002; Bernareggi, Mussio, & Parasiliti Provenza, 2009; Plimmer et al., 2011
	Occupational Skills	Wake, Wake & Takahashi, 1999; Chit & Yap, 2012
	General	Ashcroft, 1983; Bach-Y-Rita & Hughes, 1985; Locke & Mirenda, 1988; Guha & Anand, 1992; Miletic, 1994; Miletic, Hughes, & Bach-Y-Rita,

		1988; Landau, Russel, & Erin, 2006; Petridou et al., 2011; Paneels et al., 2013
Navigation	Physical Environment	Hill & Black, 2003; Zelek et al., 2003; Simpson et al., 2005; Zelek, 2005; Marston et al., 2007; Ceipidor et al., 2009; Ghiani, Leporini & Paterno, 2009; Ando et al., 2012; Wang, Li & Li, 2012; Simmonett & Ryall, 2013
	Virtual Reality	Lahav & Mioduser, 2004; Tzovaras et al., 2004; Magnusson & Rassmus-Grohn, 2005; Moustakas et al., 2007; Tzovaras et al., 2009; Thebpanya, 2010; Lahav et al., 2011; Kaklanis, Votis, & Tzovaras, 2013; Lahav, Schloerb, & Srinivasan, 2013
Computer Accessibility	General Browsing and Navigation	Ebina et al., 1999; Brewster, 2002; Edwards et al., 2005; Jacko et al., 2005; Yu et al., 2006; Kane, 2011; Al-Qudah et al., 2014
	Games	Sjostrom & Rassmus-Grohn, 1999; Raisamo et al., 2007; Bargerhuff et al., 2010

No Specified Application	Kurze, 1999; Kawai &Tomita, 2000; Kahol & Panchanathan, 2008; Williams et al., 2011; Velazquez et al., 2012; Rastogi & Pawluk, 2013; Rastogi, Pawluk, & Ketchum, 2013

Table 4 Number of Users With Visual Impairments Included in Study

Number of Users with Visual Impairments	**Number of Studies**
1-4	11
5-10	21
11-20	14
> 20	11
Not Specified	4

Table 5 Summary of Recommendations for Future Research

Optimal Device Characteristics	**Design Methodology Recommendations**
• Multimodal: providing both tactile and auditory feedback to the user is often most effective, especially for conveying complex information • Adaptable: utilizing simple and flexible platforms for a variety of different applications • Portable and affordable: using hardware platforms such as adapted touch screens or computers when possible as opposed to more expensive pin matrices and force feedback technologies • Refreshable: displaying new information rapidly and responsively • Multitouch: providing as many points	• User-centered design: Employ an iterative design process, in which users are involved in every stage of the planning and prototyping process, to ensure the final design is best adapted to user needs. • Usability testing: Test the device with at least five users with visual impairments to identify significant usability issues. • Large sample size: Test with a larger group of users with visual impairments if statistically significant results are required, or if the device will have many different applications. • Sighted users: Include blindfolded sighted users in the study design to serve a

of contact as possible and allowing the user to explore freely, ideally using both hands	clearly defined purpose, such as a pilot group or a control group.