Examination of the Level of Inclusion of Blind Subjects in the Development of Touchscreen Accessibility Technologies

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Summary/Abstract

Touchscreens have become the dominant interface for mobile devices, and mobile devices have become increasingly central to the average person's everyday life. Unfortunately, touchscreens offer little non-visual feedback necessary for blind users to fully utilize them, leading to the development of accessibility hardware and software. Unfortunately, previous research and development in these areas, particularly as it relates to the sense of touch and haptic feedback mechanisms, has been surprisingly lacking in blind participants and research on blindness itself. This paper thus aims to explore the consequences of this situation, as well as to provide a collection of relevant work on both blindness and developing touchscreen technologies. It does this by first examining how blindness interacts with the sense of touch and information processing. This is then compared with a sampling of the ongoing developments in haptic feedback technologies for touchscreens. This sample is examined for the participation of blind subjects or relevant research in order to determine the existence, nature and extent of any anomalies in participation or literature.. Application and software development is then similarly compared and both are examined for potential standardization systems that could improve their overall utility and accessibility. Following this is a look at the consequences, both documented and potential, that could stem from inadequate involvement of the relevant subjects and research. Penultimately, arguments in favor of improved development as a benefit to both blind and non-blind users are put forward. Finally, more recent research is reviewed and used to reinforce the central conclusion that, in light of the variations in information processing by blind users and the wide variety of potential software/hardware configurations, there is simply no substitute for the inclusion of blind subjects in further research and development.

Section 1: Introduction and Outline

Research and development are frequently complicated endeavors, requiring diligence and attention to detail, but even the most studious and well-intentioned researchers can miss things while designing their tools or experiments. Within the field of research relating to accessibility technologies this can be a special challenge because researchers, or commercial developers, must understand both the disabilities they seek to ameliorate and the technologies they intend to use to ameliorate them. One such combination is the exploration of how to improve the accessibility of touchscreens for those experiencing total blindness. Unfortunately there is evidence that those looking into this particular subject have not always manage to understand the interplay between the two.

This evidence was collected by examining studies for references to relevant research on the blind, blind participants, and the geographic and temporal locality where that research took place. In order to bridge some of the gaps in the research in this dissertation, it seemed logical to include a collection of research on blindness. This includes social elements, such as the formation and mitigation of biases that face the disabled in society, and the blind specifically. Also included is information on how blindness itself varies between blind individuals, in the sense that how a person has become blind impacts how those individuals take in and process information. This, in addition to the fact that tactile sensory improvements are the result of practice, are key components to understanding just how to best design technologies intended to assist the blind in accessing touchscreen information.

Touchscreens are, however, only the latest interface to mediate human-computer interactions. It may be trivial on some level, but examining the history of interfaces allows for a more complete understanding of the context within which touchscreen accessibility finds itself, considering their incredible proliferation and the paradigm shift they have driven. It also lays the foundation for subsequent chapters on standardization as a means to improving accessibility by laying out a quick guide to existing legal frameworks and voluntary guidelines intended to help the disabled retain equitable access to society and technology.

What becomes apparent as one examines all of this is that hardware development has its limitations. While touchscreens themselves provide a primary interface for the bulk of users, hardware peripherals like companion keyboards, or internal screen readers, are essential for blind users to retain accessibility. As such, it seems logical to encourage research intended to improve the accessibility of the touchscreen itself if one wishes to maximize their usability for the blind. There are some key problems with attempts to develop more advanced touchscreens, and even more problems in the research that is aimed at developing these technologies, including a failure to include blind participants, or even research on blindness such as that included within this very dissertation.

It would be remiss to assert that the failure to include the blind or research on the conditions impact on information gathering is a problem without providing evidence, to the next section does just that. It provides a selection of areas in which the current research fundamentally misunderstands blindness, particularly in how it results in improved tactile sensation. It also covers previous examinations on the blind and their interaction with accessibility technologies, and a short look at researchers that do manage to include the appropriate research. Sadly, this is not always enough to eliminate all misconceptions, though it indicates progress either way.

Where there has not been progress is in the accessibility standards for hardware. There are certainly hardware standards to be considered, either for ensuring devices are compatible with each other, or with users. Implementing revised standards could also be a means of reducing the workload on researchers to be personally familiar with blindness and current accessibility technologies. Much of this can also be applied to software research and development which presents the second main prong of accessibility research. A touchscreen is all but useless without software with which to interact. This becomes all the more pressing when one considers that some services are unavailable independent of applications on touchscreen devices. Much like in hardware, there are accessibility standards for mobile webpages, but the same cannot be said of applications in general.

Between the inattention paid to the existing research and the lack of hardware and software standards available to guide touchscreen accessibility for the blind, it is only natural to explore the consequences in terms of technology, research and the blind community itself. The blind community has, unfortunately, been cynically addressed by those offering new solutions to the accessibility issues caused by blindness. It is thus incumbent on researchers to clarify the utility of their devices and research not only to the research councils to which they answer, but also to the participants in order to build trust and ensure that the research addresses real and pressing desires within the community it attempts to service.

The final chapters focus on the benefits for non-disabled users that can be derived from research acknowledging the learned aspect of tactile sensation and blindness, as well as research that incorporates such concepts. The former is important in that it serves as a reminder that non-disabled users can, indeed, benefit from improved accessibility in both hardware and software, making the research broadly valuable for more than the minority of the population that is totally blind. The latter is that much of the more recent research not only incorporates research on blindness and the blind, implicitly supporting the notion that their inclusion is valuable, but also explicitly citing the same concerns presented within this dissertation. With that overview in mind, the following is a detailed account of the methodology involved in the development of this dissertation.

Section 2: Methodology

The overall methodological design of this dissertation is that of an overview and analysis of the state of existing research. As such several factors needed to be considered such as the timeframe accounted for within each article, the geographical region in which the research was conducted, and the methodology and conclusions of the research itself. To accomplish this, the largest possible sample of existing research needed to be collected and examined. As there are very real time constraints on the writing process, and equally real limits to reader attention, this need to have a large body of research has unfortunately been fulfilled to a more limited degree than would otherwise be ideal. Nonetheless, each element of the aforementioned areas of the documents that were examined played a critical role in determining the outcome of this dissertation's own conclusions.

The most pressing element is the final one listed, that of internal methodologies. Each study selected was examined closely for its internal design, with special attention paid to participant details. This was then compared with the literature review of the study and conclusions to attempt to uncover any direct links to the blind community either through the participation of blind individuals, through links to scholarly research on blindness, or through associations with advocacy groups. Attention was also paid to any mention within the methodology as to why these individuals or groups were, or were not, included. This was then compared to any identification of limitations created, or mitigated, by these circumstances either in the conclusions or discussions, or where applicable within the section on limitations and concerns.

The next concern was the timeframe in which the research took place. This is of particular concern because touchscreen technology has only achieved ubiquity within the last ten years. Research directly related to blindness and the use of touchscreens was noted, as were examinations of tools and accessibility aids that existed prior. Past explorations were examined to determine their specific relevance to the topic by determining their inclusion of computer technology. Those that included computerized devices were given further examination for issues caused by the devices themselves, or caused by their development methodology. Studies outside the designated chronology and technology requirements was retained in order to provide examples of the issues being examined within the larger frame of improving accessibility to technology and the external environment for the blind.

Finally the geographic distribution of research was assessed to determine the localization of any particular methodology, be it strong or otherwise. This took the form of examining not only where the research itself was taking place, but also what political or social institutions may be acting on the region. This was considered important for two key reasons. The first was as a means of determining whether or not the inclusion of the blind, or research on their ability to access information via touchscreen had any geographic leadership, or if any particular institution was making unusual progress. The second was because of the differing standards and legal frameworks that are present across the range of countries in the world, it became interesting to examine whether or not those frameworks would improve the focus on accessibility in this specific area.

Supplemental review was also done on the history of computer interfaces and their level of accessibility to the blind. This was done mostly to provide a historical context for current issues. Further review was also conducted into the nature and expressions of prejudice, particularly as it applies to the physically disabled. Of special note were the formation of biases and methods of mitigating them that might explain existing patterns of behavior within the research community. This was ultimately significant for how it connected personal connections with professional decisions. It also served as a way to establish the likely cause of any failure to include or communicate with said community, and to establish what impact it may have on the results of the research examined.

Section 3: On Blindness

Before engaging too deeply with the specifics of the interaction between blindness and accessibility, it is useful to examine accessibility in a larger context. Few people are likely to state outright that they oppose improvements to accessibility, especially in the abstract. However, when presented with the opportunity to act on recommendations aimed at improving accessibility it becomes more difficult to secure support as individuals and organizations work through their cost-benefit-analysis, which is to say nothing of commonly held, unconscious biases that exist throughout society (Allen & Birse, 1991). To that end there needs to be some examination of the underlying issues surrounding perceptions of blindness within society. This includes existing social attitudes towards the blind, their causes, and methods of mitigation. It is also important to recognize that the blind are not a singular, monolithic entity and that the differences between blind individuals can have a significant impact on how they internalize and interpret information, which is often left out of research considerations. It is also interesting to consider how blindness can cause disruptions in the interpretation of data translated from visual elements to tactile ones, as well as the limitations this places on technology intended to assist in this activity.

Bias regarding groups of individuals frequently has a historical basis (Kornberg, 2016), but research on the historical stigma surrounding blindness is somewhat sparse. This may be in part due to blindness's relatively mixed cultural treatment, wherein even gods are said to have been blind, even if individuals suffered negative treatment. Current studies, however, indicate that the biggest issue facing the blind is the misconception that they are in some way fundamentally incapable of, or incompatible with, jobs normally assigned to the sighted. A survey of managers found that a majority did not believe their organizations had placements for the visually impaired, and that they also (erroneously) believed that such individuals were more expensive to hire (Lynch, 2013). Similarly, a Canadian study (Benoit et al, 2013) found that the blind perceive significant stigma when it comes to searching for employment, which is reflected in their significantly higher rates of un- and underemployment. These prejudices, while ultimately misguided, are based at least in part on assumptions that the blind are unable to function properly in an environment designed around sighted individuals. In the medical field, blind mothers face frequent skepticism of their ability to care for their newborn children (Frederick, 2015). The reality is that whatever the situation throughout history may be, the blind still face prejudice in the world today because of the skepticism regarding their ability to interact properly with an environment built around having the sense of sight, such as touchscreen interfaces.

It is, however, notable that these biases tend to be formed in the absence of actual experience. Managers that personally knew or had experience with blind individuals were significantly more likely to see a place for blind persons within their organizations, and to consider hiring them (Lynch, 20013). In some ways, this mirrors the apparent social phenomena whereby those with the least exposure to immigrants seem the most opposed to their presence (Travis, 2016). Moreover, failures to implement accessibility options in digital spaces is at least partially a result of oversight (Freire et al, 2008). While it is problematic to allow a user group with special needs to be overlooked, being overlooked is much more surmountable than being looked down upon, and it would appear that in the digital space at least, blind users have simply been overlooked. This correlation between exposure and understanding means that it is imperative to increase awareness if steps are to be taken to improve accessibility for the blind. This should also include some awareness of the subtle differences between the different forms of blindness and how it impacts information acquisition and interpretation.

One such variation is the difference in image processing between those that have been blind since birth as opposed to those that have gone blind later in life. While sighted users and blind users ultimately process image information similarly (D'Angiulli, 2006) as long as the image is properly conveyed to both, differences in acquisition result in differences in information seeking strategies between these two user groups (Tekli et al, 2018). These differences include things like the amount of screen area a user is willing/able to explore as they attempt to follow vibratory guides, and the directions in which they move their fingers in their attempts to discover information. More fundamentally, those users that have been blind since birth have the most accurate sense of touch, which reinforces the notion that their heightened sense is the result of mandatory practice. Those with reduced vision have yet other types of exploration strategies.

This wide array in tactile strategies can make developing a single system for assisting the blind difficult (Tekli et al, 2018). This is actually compounded by the fact that visual information and tactile information can interfere with one another

(Solz et al, 2017). Thus designers may need to completely rethink how to create suitable interfaces for the blind. Even as more advanced haptic feedback offering the ability to convey complex shapes and images, the users themselves are limited by their physiology and may struggle to process the input in a meaningful way. offerings provide the ability to convey complex shapes and images, the users themselves are limited by their physiology and may struggle to process the input in a meaningful way. The fact that some researchers have limited or no contact with the existing research and community leads to misunderstandings about what their goals and considerations can reasonably be.

There are many issues facing the blind, some of them better understood than others, particularly by those that might be conducting research into assistive technologies. The best cure, as it were, seems to be simple exposure and direct interaction, meaning that there really is no substitution for their participation in research and development. This need is even more acute when it is noted that blind individuals will attain and understand information differently depending on how the condition developed. This must, however, be considered in light of the limitations of the blind and the technology they utilize, limitations best understood through careful study and experience by the blind themselves. This has not always been quite so necessary, as while the blind do require some special assistance the methods of interacting with computers have shifted over time in ways that have made interactions for the blind much more difficult.

Section 4: History of Interfaces and Accessibility Technologies

The original computers, room-sized machines that utilized cards with holes punched in them, may well have been the most friendly to blind people, offering a significantly more apparent tactile feedback system for inputs, even though the outputs would remain printed. This was succeeded by the keyboard and monitor, which offered users an identical keyboard layout to the typewriter, a device that itself blind with writing, or users could opt for a Braille keyboard. The monitor, meanwhile, allowed for text and very little else, so that when Jim Thatcher developed the IBM Screen Reader for DOS in 1986 it only needed to process letters and words just as any sighted user would. The development of the graphical user interface for the PC lead to a divergence in what blind and sighted users could interpret. While Thatcher developed the Screen Reader 2 for these new interfaces, it now needed to process images as words, which required a subsystem where the words were embedded within the icons for use with accessibility tools (Thatcher, 1994).

The graphical user interface operated by keyboard and mouse remained the dominant paradigm until the advent of the capacitive touchscreen. Touchscreens were initially popularized as a consumer product through their inclusion in personal data assistants, but slowly became the dominant standard in mobile phone interfaces with the introduction of Apple's iPhone. While the iPhone had some initial difficulties owing to a more limited cellular internet infrastructure at the time of release, as well as an imperfect partnership with AT&T (Pogue, 2007), and today there are nearly 4 billion smart phones active in the world (Daniels, 2017), as well as many more tablets and other touchscreen devices. As these devices have proliferated, so have apps for them as well as mobile web development. What has not kept up are the tools blind users rely on in order to use smart devices, which have all but remained as they were during the time of mouse-and-keyboard graphic user interfaces.

What is equally apparent is that there has been a significant and fundamental shift in the way that sighted users interact with technology, and that accessibility technologies have not kept pace. This is almost certainly not malicious, or even intentional. The blind constitute only about 0.5% of the global population (Mariot, 2010), meaning that direct connections between blind users and developers will be necessarily infrequent, which reduces the chances of the needs of blind users being addressed. Groups like the W3C attempt to compensate for this by producing and advocating accessibility standards, but it is reliant on the voluntary adoption of those standards by individuals and organizations. Parallel this, governments and other formal organizations have gradually implemented rules and regulations designed to ensure accessibility to jobs and the world at large, but to date there has been no such legislation with regards to touchscreen devices. This is all the more problematic in light of this new paradigm, and the rapid pace of technological development.

To ensure proper access to the world and society, several national governments have seen fit to pass legislation to ensure that the physically disabled are able to properly participate, such as the Americans with Disabilities Act in the United States of America, the Equality Act 2010 in the UK, or the Disability Act 2005 in Ireland. On a global level the United Nations has issued the Convention on the Rights of Persons with Disabilities. While legislation cannot absolutely guarantee that those that face bias will be relieved of the prejudicial behaviors that accompany it, it can give those that feel they have been unfairly maligned a mechanism for redressing their grievances. These legal frameworks are, however, primarily targeted towards ensuring non-discrimination in work or consumer transactions. Even if they were not, the touchscreen has soared to prominence so rapidly since the passage of even the most recent of these pieces of legislation, that there is no legal structure in place for ensuring that blind users have equitable access to an Internet increasingly designed for touchscreens.

This is why the work of non-governmental organizations, in particular organizations such as the World Wide Web Consortium (W3C), is so important. While they do not bear the weight of law, these standard-making bodies work with industries to help determine how best to develop and implement standards that can improve Internet accessibility for those without the use of their eyes. However, much like the legislation these organizations, in particular the W3C, can move quite slowly. The latest full set of W3C accessibility guidelines was issued in 2008 and still references a touchscreen PDA with physical keyboard, a device that has been all but phased out with the ubiquity of touchscreen smartphones. These groups do excellent work, and their support helps to give web and software developers guidance, but in addition to their slow issuance of guidelines there is no enforcement of adoption. Sites like Google and Facebook frequently manage only middling to above-average scores in accessibility evaluation applications (Goncalves et al, 2011).

The W3C's work primarily concerns web and, to a more limited degree, software development, giving it sway only in software interfaces. Hardware interfaces, meanwhile, continue to be developed in accordance with the impulses of the developer. While historically, hardware developments have offered some level of information parity for blind and sighted users, this has not necessarily held true in the face of the popularization of the touchscreen as a primary interface. What's more, government regulations have no means of enforcing broad accessibility standards for this new interface, and non-governmental standards have no enforcement mechanism, making their adoption voluntary and inconsistent.

Section 5: Hardware Development

Looking ahead it is clear that there needs to be an increased focus on accessibility as it relates to touchscreen devices. While there are 4 billion smartphones already in circulation, the number is expected to rise to 6 billion by the year 2020 (Daniels, 2017). At that time the UN projects the global population to reach roughly 8 billion people (United Nations, 2017), which would mean roughly 40 million blind persons potentially needing to interact with these devices. But where formal standards may be lacking, there is certainly research into improving accessibility for the blind, particularly through the use of sophisticated hardware. As such it is important to examine what tools are being put forward. Some are essentially identical to those of the past, including screen readers and keyboard peripherals. Others are more novel and geared towards making the hardware itself more accessible to blind users through tactile, or haptic, feedback. These tools have several shortcomings, but more to the point, they are sometimes developed without the appropriate knowledge or participation of blindness and blind individuals.

At their most straightforward, the most basic of these devices are new iterations of the technologies that have come before. Wired computer keyboards, and physical keyboards built into phones, have been replaced by keyboards-as-accessories, frequently reliant on wireless technologies to connect the device to the touchscreen with which it is being paired. These keyboards may be either QWERTY standard or Braille and come with an array of shortcuts, features and prices. There are also Braille reader peripherals, which will allow users to convert onscreen information into Braille text. These devices and applications are in some ways ideal. For one thing they are well understood by both the users that would be likely to need them, and by manufacturers and developers, since there is ample experience and precedent regarding what works and how well. Unfortunately, they can be more difficult to transport than a smartphone or tablet alone, though they are sometimes the only means by which the blind can navigate digital spaces on a touchscreen device, so the tradeoff is a necessary one.

Attempts to modify the touchscreen itself are a means to mitigating the transportability problem and lead to more novel solutions. Researchers have attempted to develop a wide array of prototypes for helping the blind better utilize touchscreens, with a particular emphasis on haptic feedback and vibration technologies (D'Angiulli, 2006; Tekli et al, 2018; Nishino et al, 2012; Lahib, 2018). A particularly common approach is the use of "pinboards" that render onscreen elements by using an array of height-variable cylinders (Paneels & Roberts, 2010). Another approach involves a system that modulates vibrations in order to indicate the boundaries of onscreen objects (Nishino et al, 2012). A separate facility has managed to create a system that allows users to feel variable touch sensations as they move their hand across a specialized screen intended to let users feel the contours of images (Wu et al, 2011). These systems are obviously experimental, and it is entirely probable that they will never make it to the market, but that they exist at all is an indication that there is research being done and that it is producing results. These technologies should also be of interest to sighted users, as they would provide new ways of interacting with the information displayed on their smartphones.

These ideas have two major shortcomings. The first is that they are not yet available and may never be available. While they may be an amusing novelty to sighted users, their primary value lies in their ability to improve access for the blind. Even with a global population of 35 million potential users, the target demographic is tiny, and unlike research institutions that can spend money on ideas that ultimately go nowhere, businesses will always be looking at how to cover their costs. The other major problem lies in the research itself. While the results may be interesting, the researchers are often failing to consult with blind users or their advocacy groups, or even the existing literature on blindness. This means that whatever the results, their research may ultimately be headed nowhere if it turns out that the technology fundamentally misunderstands its potential users.

Before judging too harshly, it is important to establish for certain that researchers are not making use of the existing information. The vibration-modulating interface used among the previous examples (Nishino et al, 2012) is particularly egregious in that it cited no research on blindness, no previous technology studied and used sighted participants with a disabled visual interface to test the design. The haptic image display proposed (Awada, 2012) similarly had little in the way of references to external research on blindness or any examination of previous technology. Other studies manage to incorporate the proper research, but then have such limited participation (Kammoun et al, 2011; Wu et al, 2011;) that their results would be difficult to extrapolate to a larger population of users. This is not entirely unreasonable, considering the limited availability of blind people within the general population, but this still limits the overall applicability of the studies in question. This is not the entirety of research on the topic, but this sampling is indicative of the state of research until very recently.

Section 6: Evidence of Gaps

It should be noted at this point that the these studies are but a sample, and one that is somewhat selective, but it even if it is uncharitable, it is an accurate representation of the state of research to date when one considers that only 19% of developers consider accessibility in their designs (Freire et al, 2008). Even the largest tech companies often receive only middling scores across common measures of accessibility (Gonçalves et al, 2012). Some of this is, as previously mentioned, simple oversight, but others may imagine that the technologies that are currently available are sufficient. This is primarily problematic for two reasons. The first is that existing technology is based on the flawed research that has been conducted until fairly recently. The second is that the variety of touchscreen interfaces is increasing as they occupy self-checkout grocery counters and replace physical buttons on the Mackbook Pro (Cooper, 2016). It should, however, be noted that many of the issues already mentioned, though overlooked in the research, are not necessarily new. By the same token, those that do recognize the shortcomings of existing research do not always show complete understanding of the topics of blindness and accessibility.

One seeming cause of the flawed understanding researchers seemed to have of the research surrounding blindness and the needs of the blind community is, in part, a startling disconnect between the fields involved. Visualizations of the interactions of scientific disciplines frequently show few connections, direct or even with one degree of separation, between medical science and computer science, or engineering (Börner, 2010). The divide appears to be narrowing with time, with more recent studies paying closer attention to the existing research, but this does not always enough to avoid misunderstanding. Most fundamentally is the fact that that the blind have sharper auditory and touch perception as a result of practice, which makes it a skill. Secondary issues arise as one examines the data on how the blind interpret stimuli, namely that the totally blind process information differently than the partially blind. The same goes for those that were blind at birth when compared to those who lost their vision later in life.

Moreover, these issues are not new. In 2008, Lévesque identified the seeming lack of concern for those that would potentially use the devices being designed. A Malaysian study (Muniandy & Sulaiman, 2017) from the International Conference on Research and Innovation in Information Systems identifies as a primary concern the lack of focus on the blind in studies that supposedly center on them and their needs. Rodriguez-Sanchez et al (2014), in their designs for a wayfinding system intended to allow the blind to navigate unfamiliar physical spaces make special note of failures among similar developers to adequately incorporate information about the blind and blind users themselves into their research designs. This indicates that there is some awareness of the problem, or at least sufficient to gain the attention of a small number of researchers. The good news is that there are a fair number of projects that do incorporate proper research, blind participants, or even both (Rodriguez-Sanchez et al, 2014; Lahib et al, 2018; Bonnington, 2017).

This inclusion does not always exempt these researchers from errors with regard to the finer points of blindness and how it impacts sensory perception. Sabab & Ashmafee (2016) managed to both have ample background information and yet fail to remark on the differences between the blind and the visually impaired, or how blindness impacts perception differently when acquired later in life as opposed to at birth. They do, however, correctly identify the most fundamental truth that the improved tactile and auditory perception commonly found in the visually impaired are an acquired skill resulting from practice. This observation, made also by the Wong et al (2011), is central to the understanding of how blindness can be addressed in touch interfaces because it means that designers must consider the variances and limitations that exist between blind users.

Section 7: Hardware Standards

This could, in theory, be corrected to some extent by studying the existing standards and practices in place for helping the blind access information. If tactile comprehension is, as it appears to be, a skill, then it is developed through practice and repetition. This makes the development of and adherence to standards an invaluable asset to blind users and an essential consideration for developers. For one, designing devices around the existing design conventions for assistive hardware means avoiding unintentional confusion for potential users. It is also important for developers to adhere to the more concrete standards for hardware interfaces if they intend to market or distribute their developments more widely, or the entrenched standards for things like keyboard layouts. There are also attempts to bridge the hardware/software gap by converting hardware into software applications for the touchscreen interface, but applications have no formal standards so research and development us again focus carefully on the informal conventions in order to avoid creating usability issues.

It is the learned nature of tactile interpretation that forms the crux of good design for blind users. Not only do systems need to be designed with some understanding of what users already know simply to make the adoption of new devices and applications easier, but it is also essential if developers wish to avoid making their interfaces unintentionally frustrating. Because users will almost certainly come to new devices with some form of previous experience, it is possible that without due diligence interfaces could work against users. This could be as simple as switching the positions of existing interface objects, or it could be as extreme as placing crucial objects in unfamiliar places. Indeed, the lack of application guidelines for accessibility means that this is a problem that many blind users have already encountered on a regular basis, as each application organizes its menus and file structures individually based on the whims of its designers.

One area that has very definite standards is the area of hardware interface technologies. These standards allow developers to create a broad array of devices across all ranges of functionality and prices that are certain to work with systems most consumers will be familiar with, be they physical interfaces or digital menus. In the case of hardware, most formal standards have more to do with interfaces than the devices themselves. The most common interface for mobile devices to connect with external hardware while on the go is Bluetooth, first developed in 1998 (Bluetooth

SIG, 2017) and since adopted by the majority of mobile developers, though some exclude Bluetooth functionality as a cost-cutting measure. This means that blind users must be extra cautious about their touchscreen device choices if they wish to utilize Bluetooth features. Connections between mobile devices and desktop or laptop PCs are usually mediated by USB connections, with USB micro currently acting as the standard connection on the devices themselves, and USB C being adopted by Apple (Ackerman, 2015) and other manufacturers for future devices.

Many blind users make use of connected keyboards in order to fully utilize their touchscreen devices, as the limited feedback and small screen size makes the onscreen QWERTY keyboard impractical (Harper et al, 2011). These keyboards conform most often to one of two dominant standards. Some adopt the QWERTY standard that has existed since the development of the typewriter, itself a device intended to assist the blind with writing (Thurber's Chirographer, 1847). The other common standard is the Braille keyboard, which has a set of six primary buttons used to generate letters and numbers. These are often paired with some kind of screen reader or other auditory feedback mechanism that allows the user to hear what they've typed for certainty. These devices have formal standards, but their designs are also so ubiquitous that deviation from them frequently results in negative user feedback (Shapiro & Varian, 1999). For Braille keyboards and screen readers, there has also been progress in converting the hardware into touchscreen applications (Bonnington, 2017).

Humans develop tools to fulfill specific tasks, and assistive technologies for the blind are no different, but what is often overlooked is the role of practice in the utilization of tools, and in the adoption of new tools. The QWERTY keyboard is an example of an entrenched standard in part because everyone has built their competence around that specific keyboard configuration. The same applies to Braille keyboards, and to their credit both hardware peripherals and touchscreen applications adhere to the standard eight-key format for Braille keyboards. What is not understood is how knowledge of this standard might impact the ability of users to understand and utilize more novel interfaces. Tactile sensation is enhanced in the blind as a function of practice, and they practice most commonly with Braille keyboards or screen readers, which means that future development should be designed, ideally, in such a way as to make the change from these devices to newer applications as seamless as possible.

Section 8: Software

The most important piece of hardware is still the touchscreen itself. Keyboards and screen readers are designed to mitigate the general lack of tactile information provided by touchscreens. The research and development of novel touchscreen feedback for the blind is in part to allow the blind to use these devices without a mediating peripheral. This is then paired with the development of software applications for improving the accessibility of touchscreen devices, including braille keyboard and screen reader applications. This is in part because a touchscreen is useless without some kind of software for it to control. These applications are often lacking in standardization and can be confusing, even for sighted users (Harper et al, 2011).The challenge of application standardization and accessibility becomes all the more pressing once it is noted that some services are only available via applications on touchscreens. Other technologies, particularly virtual personal assistants, have been developed without the blind specifically in mind, that could nonetheless help with these issues. Another imposrtant area of software development is website accessibility for touchscreens. There are standards in place for webpage accessibility generally, but much like virtual personal assistants there are some critical flaws that need addressing.

Application-based implementations of existing systems are one means of assisting the blind in accessing touchscreen devices. There is a Braille keyboard that centers itself on the user's fingers (Bonnington, 2017). Other applications allow users to utilize screen reader functionality on their tablets or smartphones, though both iOS and Android have screen reader functionality by default. VoiceOver and Talkback, enable a suite of accessibility options, such as text-to-speech and an array of vibration and sound cues to help the visually impaired navigate the touchscreen environment. These platforms offer a way for users to more readily take advantage of touchscreen portability, removing the need for an external device. They do, however, require additional development time because while the functionality is identical, the implementation is quite different.

These added accessibility options become more pressing when one realizes that certain common functions are only usable through applications, such as Facebook's Messenger service, used to allow users to communicate directly and privately. On mobile devices it is completely inaccessible without the use of the

Messenger application. Absent enforceable external standards, the only way that the Messenger application will have accessibility features is if Facebook decides to include them. It should be noted that Facebook has included support for screen readers within the application and provided detailed usage information on their Help page, but Facebook's screen reader support is its own, as is its implementation of the underlying code that facilitate screen reader usage.

That is not to say that there are no conventions in terms of application design, but they are often only that: conventions. Developers are left to decide whether or not they wish to adhere to them, and those that choose to deviate are rarely doing so with significant concern for the impact their design decisions are likely to have on blind users (Freire et al, 2008). This is a problem that is further exacerbated by lax webstore policies on the part of platform developers like Google, though even Apple's iStore does not have any formal accessibility guidelines for developers. Those applications that do intend to improve accessibility then need to have options that are clear and similarly organized if they are to ensure maximum usability. This requirement exists in tension with the need to innovate in order to make easily distinguishable products in a highly competitive environment.

Similarly to the development of services like Talkback and VoiceOver, the development of virtual personal assistants found across a wide spectrum of smart devices also offers improved accessibility for blind users hoping to make use of their touchscreens (Coetzee & Olivrin, 2012). These were not developed specifically to help the visually impaired, but their ability to use voice input and give audible responses makes them inherently useful to users without sight. These personal assistants are also present in a collection of non-touchscreen devices, such as smart speakers that can control a household's worth of connected smart devices, which would have previously required an individual app for each device, each with its own accessibility issues. This not only streamlines a cumbersome interface for sighted users, but it means that the blind may also adopt smart home technologies should they be so inclined.

That is not to say that virtual assistants are perfect, and misunderstanding a user's speech is a regular problem. When Microsoft launched its virtual assistant, Cortana, and included it with their Xbox One video game console, users often complained that it couldn't understand them. Particularly frustrating was its apparent inability to understand certain accents (O'Dwyer, 2013), meaning that even those users what had a supported language could never be sure their specific pronunciation would be understood. On the other side, Amazon's Alexa could be activated by any sound source producing its trigger word, resulting in unwanted searches for items advertised on TV in nearby rooms (Sky News, 2018). As time has passed these complaints have subsided, but it is unclear if that is due to improvements in the technology itself, or users becoming accustomed to the service's quirks.

Unlike applications, there are much more extensive guidelines aimed at improving web accessibility, with the most comprehensive formal standards being the Web 2.0 guidelines from the World Wide Web Consortium. There are, however, some key issues with their adoption. For one, the standards themselves are out of date, still referencing touchscreens and physical keyboards on personal digital assistants like the Blackberry (WAI, 2017). For another, the actual rate of adoption for the standards outlined therein have not been particularly good (Gonçalves, 2012). This leave blind users in something of a difficult situation. Even if hardware and apps aimed at mimicking hardware make strides at improving the accessibility and usability of touchscreen devices for mobile users, webpages on the Internet are frequently designed without the necessary hooks to facilitate full utilization. For apps, meanwhile, the only standards are those set out by the stores they wish to operate within and those that the developers set themselves. In the cases of converting screen readers and Braille to touchscreen applications this is relatively straightforward, but for the more novel approaches there is little in the way of advice for applying the logic of current standards to new devices.

Touchscreens are a unique and pervasive interface, but they are not particularly useful without some kind of software. Some applications are designed around implementing existing interfaces, like keyboards and Braille inputs directly through the touchscreen. Other applications are services, some of which cannot be accessed through alternative methods. Others are alternative interfaces altogether, like the virtual personal assistants, and while none of these are perfect, many of them do improve accessibility on some level. The crucial problem is that these applications and software are developed largely independently of any existing standards. There are web development guidelines, but the most recent formal guidelines are outdated and lack any method of enforcement. What may be needed in order to maximize application accessibility are standards, either formal or informal, but broadly accepted enough to allow users full benefit of the learned nature of the tactile acuity developed as a result of blindness.

Section 9: Complicating Factors for Standardization

Within both hardware and software development, standardization is a valuable tool in engineering and design, but it is doubly so in a situation where users understanding and interpretation is based on practice and repetition. There are some formal hardware standards, but those that most relate to the actual mediation of interactions between the blind and their touchscreen devices are those that are entrenched in the actual layouts of the keyboards, though the variable availability of Bluetooth is always a point of concern. There are also formal guidelines established by the W3C for the development of accessible websites. Sadly, these standards are out of date and are inconsistently applied. Application development, on the other hand, has virtually no accessibility standards and the environments can, and often are, a point of confusion and frustration for blind users. There is a space for developers in this area to work both with one another, and with the blind community, to develop some truly novel and powerful tools for navigating a world increasingly dominated by touchscreen devices, but it is up to all parties involved to actually communicate and find a way forward.

One issue that can make standardization difficult across both areas is the fact that not only is the raw number of touchscreen devices in use substantial, but so is the variance between them. From differences in hardware specification to variations in the very operating systems that power the devices, there is a staggering amount of potential variety that needs to be taken into account when developing for touchscreen devices. Amazon products, for instance, run on proprietary hardware and operate on a modified version of Android to which Amazon alone has complete access. This means that anyone that wants to design applications for Amazon products needs to have the technical documentation from Amazon, including the standards for enabling accessibility features. This would be good practice anyway, but the fact that Amazon's Android variant is updating independently of the main Android branch makes it essential.

This wealth of variation across the touchscreen device landscape creates two problems. Without sufficient standardization, development can become a confusing mess for developer and users, but doubly so for blind users who must operate in a space based on much more strict assumptions than those of users with sight. Indeed, there is evidence that failure to conform to standard interfaces and layouts in application design has rendered much of the touchscreen environment a confusing mess for blind users (Rodriguez-Sanchez, 2014). The second problem is that this means that in order to develop new interfaces and applications, developers must be personally familiar with the applications that already exist and decide if they wish to conform to design decisions already made, or if they think their own design is superior. In a situation in which countless applications are added to the market every day, and in which developers are already proven to be lacking insight into existing practices, the prospects look rather grim.

The scope of variation and lack of standards is not without its potential benefits. For instance, it presents developers and researchers with increased opportunities to find novel ways to solve the problems facing blind touchscreen users, and to interact with one another. Bridging the gaps in between medical and computer science will not occur if researchers do not talk to one another. If they do not talk to advocates for the blind they cannot adequately refine their technology to make it useful. Having no standards to reference creates, at least on some level, a space for engagement that can be absent in fields with stronger standardization. It also allows for some latitude in experimentation. While usage is skill-dependant, and the blind will have a certainly level of expectation about how their devices are setup and operated, the lack of more formal standards means there is less formal expectation to conform to them.

Section 10: Consequences

These opportunities are often not explored to their fullest potential as a result of some unfortunate, if not unexpected, consequences born of previous negative experiences between the blind community and marketers, as well as a sense that the research to date has been focused primarily on finding products to market to the blind community. This is in part because the blind often see such assistive technologies as trying to solve problems that do not need addressing. To combat this it is important to establish the utility of research devices and topic to blind participants and the blind community at large. Even so, research continues, but if there is no commercial application readily available then it falls to academic institutions, with all the pros and cons that come with them.

The situation within the research and development space is improving with regards to the integration of both standards and the blind community itself, but this has been hampered by significant damage already done between the research and blind communities. The blind are still somewhat wary of attempts by researchers to develop new solutions to their existing problems after an explosion of failed electronic navigation aids entered the consumer market in the 1980s (Lévesque, 2008). This antipathy, while understandable, does make including the blind directly in research more difficult. As such it becomes even more imperative that researchers not only ensure that they have done adequate research into existing standards, but also into existing problems, and that they can convey their understanding to participants

This is in some ways a natural consequence of the way research and development is structured, both in academic and commercial institutions. Research designs focusing on a specific technology or solution are significantly more likely to gain the attention and approval necessary to advance, while research into more general or esoteric topics can struggle to find sponsorship. This is partially because the results of research into the impact of a specific device or application are more easily quantified. It is much easier to assert and prove that this iteration of the screen reader is more effective than Y, than it is to prove the more general, yet accurate, assertion that blind people have improved senses of hearing and touch as a result of extensive practice.

The former has already been examined at some length, but that leaves the latter. One of the things that lead to the failure of the various electronic navigation aids was that it was solving a problem that did not need solving. The blind already had many ways to navigate the world, some as simple as the elongated walking cane, or as complex as direct human or animal assistance. That in combination with an increasing emphasis on public systems for improving accessibility made the electronic navigation aid redundant. Researchers would thus be well advised to make sure that their participants see the value in their proposed technologies. Considering the specific challenges associated with the extremely visual interface of the touchscreen, this could be both simple and challenging. It is simple in that the growing ubiquity of the devices means that having proper accessibility options is increasingly important. The challenge is finding ways to explain what can frequently be complex, technical solutions in a way that makes its value clear to participants and potential users.

Failure to adequately establish the utility of the device or the research, both previously and currently, has alienated some segment of the blind community. This has had the unfortunate effect of shrinking an already small pool of potential participants (Lévesque, 2008). While not specific to research on the blind, without people to participate in research or test devices, it becomes all the more difficult to say with certainty that a given development will be more broadly applicable. As it applies to research on the blind in particular, those blind since birth will have greater tactile acuity than those that have gone blind later in life, meaning that something that works for one group may not work for the other (Tekli et al, 2018). Establishing broad applicability is especially important in researching applications, which will be available to users across the entire planet through online stores.

These issues are not all easy to solve. Correctly applying standards and norms when the only way to discover them is through direct research and exposure means that it is significantly more difficult for researchers to incorporate those norms blind users already expect into their designs. This in turn makes it more difficult to prevent unintentional alienation and the attendant deterioration of relations between those designing tools and those who would theoretically benefit from them through a combination of avoidable frustration and an impression of apathy on the part of the tool's creators. This reduces an already reduced pool of potential participants, making further research and development even more difficult in a vicious cycle that, if left unaddressed, could bring all research into the topic of accessibility options for the blind to a halt, not just as it applies to touchscreens, but across the board.

There is one final complication that can result from all these cascading issues and it is perhaps the most problematic of all, and that would be a failure in sponsorship. A direct consequence of previous research focusing so heavily on specific devices and applications is that it has given the blind community a sense that they are viewed as little more than a market demographic to be exploited (Lévesque). This has reduced their willingness not only to participate in research, but also to experiment with new products and assistive tools. This in turn has reduced the market for those assistive tools, which in turn reduces the interest of commercial enterprises in exploring these projects. This leave the brunt of the work to be performed by academic institutions, where ultimate commercial viability is not necessarily a concern.

This presents its own set of problems. These institutions do not necessarily need to concern themselves with the financial viability of their research, but that also means that research can develop along lines that do not ultimately contribute new tools to assist the blind in navigating the touchscreen space. This is either because the software being tested is so specialized that it cannot be properly adapted to fulfill a more general purpose, or that the hardware is so unusual that it cannot be mass produced. It would be great if every touchscreen could support haptic feedback to such a degree that the system devised by Nishino et al. could be implemented across all touchscreen devices, but hoping that each manufacturer will voluntarily adopt such displays just to gain appeal with less than one percent of the population is impractical.

Section 11: Benefits for Non-Blind Users

As such, it is important to consider the developing state of affairs and find alternative incentives for continued support of investigations on the accessibility of touchscreens for the blind. Improved haptic feedback systems that incorporate the idea that tactile sensation is learned could potentially be of use to non-blind users, both those with other visual impairments and fully sighted. Non-disabled users can experience impairment caused by environment or device design, something that could be improved with design focused on improving accessibility for the permanently disabled. The ability to better use phones without looking could, in theory, improve public safety by reducing the level of distraction caused by mobile touchscreen devices. There are direct health benefits to be found in reducing the strain caused by constantly holding smartphones in viewing position. It may even pose some fringe benefits in improving the population available for sampling by producing more users with enhanced tactile acuity.

For researchers looking for extra ways to justify their research, there is the notion of mobile device impairment, where non-disabled users experience usage impairments as a result of device designs and/or environmental factors (Harper et al, 2011). While this impairment is obviously temporary, it is caused by some of the same root causes as inaccessibility for the blind, and as such solutions for one could conceivably lead to improvements for the other. There is also a not entirely superficial argument in favor of improving accessibility to reduce distraction in non-disabled users. Smartphones in particular are proven to be extremely distracting (Hyman et al, 2009), which can become a problem in public spaces. Improving the vibratory functionality of screens and devices to facilitate haptic images or the sensation of edges around icon borders does make it easier for sighted users to use their devices.

There are also other health issues to consider, like the complications that can arise from excessive smartphone use (Saffer, 2009). Some of these could actually be mitigated by improving and alerting users to accessibility features, since the primary injuries are caused by holding the device in a certain way or repetitive stress-related discomfort and nerve damage (Patel et al, 2017). There are also the non-health issues related to sighed users suffering from mobile device impairment as a result of device designs and/or environmental factors, which requires a similar set of solutions to those required by blind users anyway. It is always important to keep blind users in mind, it can also be beneficial to consider ways in which developments designed to improve their experience can also improve the health and experience of sighted users, if only to convince sponsors to support further research and development.

It is also conceivable that enabling such sightless usability for sighted users could, to a very limited extent, improve the potential sampling population for future research by creating another set of users with improved tactile sensation and practice with touchscreens. The most recent research certainly seems to have acknowledged the shortcomings created by a failure to involve the blind. Whether through simple inclusion of more participants (Rodriguez-Sanchez et al, 2014; Sabab & Ashmafee, 2016;), or by direct admission to sharing the concerns expressed herein, researchers are beginning to take steps to better incorporate the blind into their methodology. This research also seems to be producing results that are not only more applicable across a broader section of potential users, but also seems to be producing more interesting results by bringing forward issues that previous research had not encountered as a result of its reliance on limited sample sizes or blind users impersonating the blind.

Section 12: Research Opportunities and Improvements

Touchscreens are probably going to be a key interface for the foreseeable future, especially as the technology expands into other areas and replaces more conventional interfaces. This has already proven to be a problem on some level for the blind, but there are also unique opportunities created by the common devices to which they are affixed. The most recent research on touchscreen accessibility, however, displays significant progress in both its understanding of blindness and its willingness to test with genuine blind subjects. In an ideal world, these trends will continue, and even gain momentum going forward as a means of mitigating the complications created for the blind by the spread of touchscreen technology through society.

Unfortunately this potential opportunity for cooperation and co-development does nothing to address the problems created by the ongoing lack of standards, or continued inattention to ongoing research and development. There are real risks associated with pursuing specific technological developments without due consideration for those that they are ostensibly designed to assist. Tools developed devoid of sufficient research on the part of the creators can actually work against the user by violating what few norms they may have come to rely on. This can, in turn, lead to a deterioration in relations between researchers and the blind community as a whole by creating the impression that those making the tools do not care sufficiently about those that would use them. This deterioration can also lead to a reduction in the potential pool of people willing to participate in future research.

This is somewhat offset by the fact that Touchscreens offer something unique in that they are almost universally connected to the internet, or are easily connectable. This opens up new research opportunities by allowing participants to test accessibility options remotely. This, obviously, leads to other difficulties in research design, as it is impossible to control environmental factors for remote subjects, but with so few potential participants it becomes important to make their participation as convenient as possible. It is also possible that allowing them to participate in a natural environment would lead to more accurate findings since no amount of laboratory testing can account for the myriad complications that await users in their everyday lives. This is especially important for applications relying on touch or auditory information, which require additional concentration, even when sight has been completely eliminated.

Even if researchers choose not to take advantage of these features, and they would have perfectly valid reasons not to, it is worthwhile to make note of recent improvements in the state of research. Within the last four years researchers have sought to incorporate more research on the subject of blindness and more blind participants into their research designs (Sabab & Ashmafee, 2016), some even citing the very issues raised within this dissertation (Beteman et al, 2018; Rodriguez-Sanchez, 2014; Muniandy & Sulaiman, 2017). While this does not always result in perfect comprehension of blindness itself, or the issues facing blind users, it does indicate increasing awareness of the limitations created by failing to incorporate actual blind subjects. While the inclusion of increased numbers of blind subjects implicitly supports the notion that their inclusion is desirable, that other recent researchers have noted identical issues with regards to how the blind interpret information and the complications arising from their exclusion makes this explicit.

Ideally, this trend will continue as more research is conducted. For one, it is important for ensuring that the devices and software tested have the most accurate and applicable possible results, but also because the increased presence of blind participants can lead researchers down more varied lines of inquiry. Increased familiarity with blind people increases an individual's familiarity with their capabilities and limitations, meaning that the errors that persist in the current research (Sabab & Ashmafee, 2016) would hopefully decrease in frequency as time passes. The blind, meanwhile, would have direct access to researchers, to whom they could pose questions or make suggestions for other topics of interest. This is not a guaranteed outcome by any means, but it is a probable one, if optimistic.

Section 13: Conclusions and Limitations

Initially, this paper was to be an exploration of the current research and existing accessibility tools available to the blind in order to allow them to utilize touchscreen devices, particularly with regards to mobile internet. However, it was discovered in the course of the initial survey of literature that some of the research, especially pieces concerning the development of new hardware, frequently lacked references to research on blindness, and in some cases blind participants. So the subject changed and instead became an exploration of the impact of these decisions on the validity of the research results. To this end the existing research was examined for mentions of blind participants or relevant research on blindness, as well as when and where said research was conducted in order to ascertain the geographic and temporal distribution of these mentions, or lack thereof.

Now, to make things as simple as possible, there are two core reasons as to why this dissertation exists. The first is to identify a key gap within the body of research that deals with improving touchscreen accessibility for the blind, particularly when it involves the development of new hardware interfaces. This is particularly relevant in light of more recent research, some published during the writing of this very paper, both implicitly and explicitly support the conclusion that inclusion of the blind, and research on blindness, is a worthwhile addition to accessibility research. The second reason is to collect a body of data on both blindness and touchscreen accessibility for blindness in order to make it easier to avoid these types of shortcomings in the future.

In this, time definitely plays a factor in the amount of research available on each topic. As mentioned in Section 3, blindness has been acknowledged as a condition for so long that even mythological figures experience it. As such there has been ample time to develop a robust body of research on its causes and consequences in terms of information handling. It has unfortunately also meant that there has been a long time for unresearched opinion to become entrenched, leading to bias and misunderstanding. The most problematic of these opinions, as it pertains to the central topic, is that the blind are fundamentally incompatible with an environment designed for the sighted (Lynch, 2013). While it is reassuring that simply having direct personal experience with blind individuals can remedy this misconception, it is not always reasonable to expect any given individual to have that kind of connection considering the numerical paucity of the blind as a proportion of the population. To that end, Section 3 is meant to serve as an overview for any interested arty so that they might be able to better consider and engage with the blind community.

Section 2 serves a double purpose in that it also provides information on how blindness impacts information processing. It is important to not, for instance, that tactile sensation conflicts with image processing in the brain, even as, or perhaps because they are processed similarly. This would be a key consideration in the development of haptic imagery technologies, such as those described in Section 5. It is also considered common knowledge that the other senses sharpen in compensation for the loss of sight, but this is due to the practice being blind makes mandatory. In theory, sighted users could have similar levels tactile acuity with practice and indeed, even without that there are benefits for sighted users in this form of research (Section 10).

Understanding this aspect of blindness is essential not only in the development of hardware (Section 5). Many blind users already rely on external hardware, such as physical QWERTY or Braille keyboards, in order to make full use of their touchscreen devices. This is then paired with screen reader software, either provided within the operating system or downloaded separately. Because of this, there are existing expectations for the blind that will impact their ability to learn and understand new types of interfaces. There are also limitation to what the blind can feasibly process when again considering the way that touch and image processing can interfere with one another. These same principles apply to those seeking to develop applications intended to improve touchscreen accessibility (Section . An on-screen Braille keyboard requires little learning as long as developers make the proper affordances, such as centering the board on the user's fingers rather than on a specific point on the screen (Bonnington, 2017).

Lacking in both instances is a set of adequate guidelines that would enable researchers and developers to design tools without needing more specific knowledge about blindness (Section 7, 8). There are certainly no statutes mandating touchscreen accessibility, offering guidelines, or an enforceable penalty regimen in the way that there are for ensuring physical accessibility to buildings or equitable access to employment (Section 4). And while organizations like the W3C offer accessibility guidelines for webpage development, these are already dated and they offer no such guidelines for application development, leaving it to developers to understand and ensure accessible design.

The absence of such guidelines, and failing to incorporate either the blind or research on blindness makes it all the more possible to design tools that the blind do not want, need, or cannot use (Lévesque, 2008). As outlined in Section 10, this can have cascading consequences for those seeking to design accessibility tools. First and foremost, if proper attention is not given to ensuring that whatever tools are developed are sufficiently useful and relevant, it can alienate the very people that researchers and developers aimed to help. Those alienated people are not only disinclined to use the tools developed, but also to participate in future research (Lévesque, 2008). This can then lead into a vicious cycle where a dwindling demand on the part of the blind community can drive private investment away, sequestering the research to academic institutions that may or may not ever produce results that would be applicable to consumer products.

Section 13.1: Limitations

With all the criticism being offered, it is only fair to direct some of it internally. This dissertation is necessarily limited by the realities of time and human attention, and several of the subjects addressed have not been given the fullest possible consideration. In particular, the space afforded to the research on blindness (Section 3) itself is likely too little if this dissertation is truly to offer any kind of bibliographic functionality for future researchers. What has been presented is mostly directed at reinforcing the point that tactile sensation is enhanced in blindness not as a function of blindness itself, but as a function of practice, that it is learned. This will doubtless be a redundant notion for anyone coming to this topic with a significant background on the topic, just as much of the examination of hardware standards will be wasted on anyone with any significant degree of knowledge on hardware development.

This dissertation is intended as a means of bridging the gaps between those two groups in order to address a perceived gap in the existing research on touchscreen accessibility. It is not meant to do anything other than identify a problem and offer some research that could be used as a starting point for those wishing to address it, and to outline the consequences of failure to do so (Section 10). As such, a surface-level explanation of topics is natural, if unfortunate, and given more time and more researchers, a more thorough and more useful study could certainly be produced, but this should be sufficient as a starting point, both for that further study and for those seeing to avoid the pitfalls of earlier research.

Section 13.2: Timeliness

The examples used to call attention to the lack of blind participants and relevant research within research and development may seem like outliers, but more recent research has confirmed them to be representative of the research conducted to date (Beteman et al, 2018; Rodriguez-Sanchez, 2014; Muniandy & Sulaiman, 2017). One study (Beteman et al, 2018) even cites the exact same concerns with regards to ignorance of the learned nature of tactile interpretation, as well as ignorance of the way blindness is acquired impacts information gathering strategies within its justification. Even ignoring explicit criticisms of previous research, an increasing number of researchers are making the effort to include blind participants (Lahib et al, 2018; Sabab & Ashmafee, 2016; Bateman et al, 2018), which provides an explicit endorsement of the critique. Some of this research was even released during the production of this very dissertation, accentuating the relative recentness of these developments.

In a way this is completely logical, considering the rapid adoption of the touchscreen as a primary interface (Section 3), but the central point remains that there is no substitute for the direct involvement of the blind. They are the best equipped to know whether or not a given tool or discovery is to their benefit, and their participation is the only way to guarantee that the full spectrum of exploration strategies and information processing is taken into account. Recent research is making progress in this regard, and as a result is yielding results that are both more useful and more broadly applicable (Bateman et al, 2018; Rodriguez-Sanchez et al, 2014; Sabab & Ashmafee, 2016). Ideally this will encourage other researchers and developers to follow suit, creating a virtuous cycle of improvement and helping reverse some of the damage caused by previous, overzealous attempts to sell assistive tools to the blind community.

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