International Journal of Human–Computer Interaction

ISSN: 1044-7318 (Print) 1532-7590 (Online) Journal homepage: http://www.tandfonline.com/loi/hihc20

Visual Impairments and Mobile Touchscreen Interaction: State-Of-The-Art, Causes of Visual Impairment, and Design Guidelines

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Abstract

This paper identifies, catalogues, and discusses factors that are responsible for causing visual impairment, of either *pathological* or *situational* nature, for touch and gesture input on smart mobile devices. Because the vast majority of interactions that we have with touchscreen devices are highly visual in nature, any factor that prevents a clear, direct view of the mobile device's screen can have potential negative implications on the effectiveness and efficiency of the interaction. This work presents the first overview of such factors, which are grouped in a catalogue of *users*, *devices*, and *environments*. The elements of the catalogue (*e.g.*, psychological factors that relate to the user, or the social acceptability of mobile device use in public that relates to the social environment) are discussed in the context of current eye pathology classification from medicine and the recent literature in Human-Computer Interaction on mobile touch and gesture input for people with visual impairments, for which a state-of-the-art survey is conducted. The goal of this work is to help systematize research on visual impairments and mobile touchscreen interaction by providing a catalogue-based view of the main causes of visual impairments affecting touch and gesture input on smart mobile devices.

Keywords: touch input; visual impairments; eye pathology; situational impairments; touchscreens; mobile devices; smart devices; taxonomy; catalogue; gesture input; touch gestures; state-of-the-art; survey; design guidelines.

1. INTRODUCTION

Smart mobile devices have become mainstream in developed and emerging economies, with 2.08 billion smartphone users estimated worldwide for 2016 (Statista, 2016). Today's prevalence of smart mobile technology, now including smartphones, smartwatches, smart wristbands, and augmented reality glasses, has been enabled by significant advances in computing, sensing, and communications technology (*e.g.*, faster CPUs, larger RAM, faster and cheaper communications, and a variety of on-board sensors that detect human input and track human activity, all miniaturized into tiny form factors), but also by recent notable advances in software and touch user interface design. For instance, assistive applications have made touchscreen devices more accessible to people with visual impairments, helping them to accomplish everyday tasks easier (Chen et al., 2012; Poláček et al., 2012; Bischof et al., 2012; Brady et al., 2013). Notable examples are VoiceOver, the gesture-based screen reader built into Apple's iOS devices (Apple, 2016) or Google TalkBack for Android (Google, 2016b),, designed to improve accessibility of on-screen visual content with text narration. Also, recent efforts (from 2016) have been undertaken by Twitter and Yahoo to caption photos and videos for their users with visual impairments (Larson, 2016a,b), while Facebook has recently launched an object recognition technology that automatically produces alternative text for photos accessed in the social network by people with visual impairments.

However, despite advances in screen reader technology, people with visual impairments still face accessibility challenges (Park et al., 2014; Leporini et al., 2012; Kane et al., 2011a; Kuber et al., 2012), because even the state-of-the-art screen readers are not suited for complex tasks (Leporini et al., 2012), do not handle well inaccurate touch input behavior, such as simultaneous touches (Goh and Kim, 2014), may create a mismatch between the on-screen visual layout and the order in which information is presented to the user (Tomlinson et al., 2016), have limited features and present difficulties for accessing content in a discrete manner (Kuber et al., 2012), and, overall, do not scale well to large touchscreen surfaces (Kane et al., 2011a). Consequently, people with visual impairments still need to adopt workaround strategies to be able to use touchscreen devices effectively and independently (Kane et al., 2008a, 2009; Shinohara and Tenenberg, 2007), for which better assistive technology has yet to be presented. Moreover, on-the-go everyday use of smart devices puts even people without visual impairments in situations where they cannot have a clear, direct view of the device's screen, which makes them temporarily affected by "situational impairments" (Sears et al., 2003; Barnard et al., 2007; Abdolrahmani et al., 2016). Whatever the cause of visual impairment, pathological or situational, mobile devices must be made more accessible to their users (Wobbrock, 2006), where today's reason for poor accessibility is touch input techniques that require users to visually locate objects on the screen.

Because smart mobile devices expose touchscreens not adapted to non-visual input, the design of touch and gesture interactions for people with visual impairments demands user-centered approaches (Krajnc et al., 2010; Wobbrock et al., 2011). There have been many efforts in the community to increase the efficiency of perceived on-screen visual content (Frey et al., 2011; Guerreiro et al., 2008; Kane et al., 2008a; Encelle et al., 2011) and to improve touch and gesture input efficiency for people with visual impairments (Azenkot et al., 2012a; Guerreiro et al., 2011; Oliveira et al., 2011; McGookin et al., 2008; Wall and Brewster, 2006; Kane et al., 2013b; Sánchez and Aguayo, 2007). However, there is still a lack of understanding of how people with visual impairments attend visual targets and perform touch gestures on such devices, not to mention that the visual challenges in the everyday lives of people who are blind are still not well understood (Brady et al., 2013). Also, only recently has the community started to examine accessibility challenges experienced by people with low vision (Szpiro et al., 2016a,b). The impact of situational impairments on users' touchscreen interaction performance has also been insufficiently studied, where previous work only addressed punctual use cases, such as the effects of walking or encumbrance on mobile touchscreen interaction (Ng and Brewster, 2013; Schildbach and Rukzio, 2010). Recent work that examined situationally-induced impairments for people who are blind (Abdolrahmani et al., 2016) revealed even more accessibility challenges that need to be addressed in the community in order to provide universal access to mobile devices.

This work provides the first overview of *causes of visual impairment* for mobile touch input to help systematize research on visual impairments and touchscreen interaction. Because touchscreen input is predominantly a visual task, visual impairments, either pathological or situational in nature, will negatively affect interaction effectiveness and/or efficiency. Figure 1 shows a few examples of how various pathological eye conditions can modify one's perception of visual stimuli, such as those presented on a mobile device, causing perception to be inaccurate or incorrect, *e.g.*, glaucoma leads to peripheral vision loss (Figure 1b), while age-related macular degeneration affects central vision (Figure 1c). Figure 2 illustrates some of the causes responsible for situational visual impairment, such as occlusions of the device's display or screen glare. These scenarios are only a few examples of many possible situationally-induced impairments, and it is easy to imagine more such examples. However, no rigorous inventory of such scenarios, or of the factors that determine them, has been conducted until now, despite the benefits of such a rich source of information for researchers and practitioners designing for accessible touch and gesture input on mobile devices. Consequently, the effort to identify, examine, and catalogue causes of visual impairment is timely in order to systematize research on visual impairments in the specific context of mobile touchscreen interaction. Furthermore, design guidelines for assistive input on mobile devices, including touch and gesture input, are dispersed in the literature and available evaluations of touchscreen performance from the accessibility literature have little connected to the state-of-the-art techniques in gesture analysis (Anthony et al., 2013; Nacenta et al., 2013; Rekik et al., 2014; Vatavu et al., 2014, 2013; Wobbrock et al., 2009). Thus, we also review in this paper design guidelines for accessible touch input on mobile devices.

The contributions of this work are as follows: (1) the first survey of mobile touchscreen interaction for people with visual impairments, organized around accessibility problems of touchscreens, evaluations of users' touch input performance, and assistive input techniques; we equally provide an overview of pathological causes of visual impairment, as catalogued by the World Health Organization in the most recent International Classification of Diseases (WHO, 2016) and also an overview of situationally-induced visual impairments; (2) a taxonomy of causes of visual impairment when interacting with mobile touchscreen devices, which we catalogue on three distinct dimensions: *users*, *devices*, and *environments*; and (3) a summary of design guidelines available in the literature for designing accessible mobile interactions for people with visual impairments. We hope that this state-of-the-art survey on visual impairments and mobile touchscreen interaction will help toward systematizing research efforts in this direction and crystallize today's challenges toward new designs of better assistive technology for both pathological and situational visual impairments.

2. TOUCH AND GESTURE INPUT ACCESSIBILITY ON MOBILE DEVICES FOR PEOPLE WITH VISUAL IMPAIRMENTS: A SURVEY

Visual impairment is defined as a functional limitation of the eye(s) or the visual system that can manifest in various ways, such as reduced visual acuity, reduced contrast sensitivity, visual field loss, visual distortion, etc.; see Figure 1 for a few examples of visual impairments caused by various eye conditions. This section overviews previous work that examined the effect of visual impairments on users' efficiency to interact with mobile computing devices (*e.g.*, how well do people with visual impairments perform basic tasks on touchscreens?), as well as prior work that designed techniques to increase the effectiveness and efficiency of people with visual impairments to interact with mobile devices (*e.g.*, assistive techniques for target acquisition, software magnifying tools, gesture sets designed for people who are blind, etc.). A large body of work exists on making computers more accessible to people with visual impairments that covers a wide range of devices and techniques, from devices that output Braille or understand Braille input (Lévesque et al., 2005; Manohar and Parthasarathy, 2009) to software-based techniques designed to increase users' visual acuity of on-screen content (Turunen et al., 2010), printing techniques and special paper (Wang et al., 2012), screen readers (Sagata et al., 2007; Google, 2016b; Apple, 2016), custom web page designs (Kim and Lim, 2011; Rotard et al., 2008; Yang and Hwang, 2007), computer vision tools to assist human vision, perception, and understanding of the environment (Jafri et al., 2014; Manduchi and Coughlan, 2012), and techniques that exploit sensory substitution to render visual content in non-visual ways (Miller et al., 2007; Meijer, 2016). For a comprehensive treatment of such techniques for *any* computing platform, we refer the reader to previous surveys from the literature, such as (Hersh and Johnson, 2008; Pawluk et al., 2015; Zhang et al., 2008). With respect to mobile devices, Csapó et al. (2015) provided an overview of assistive technologies with focus on applications, such as text and speech input, navigation, and gaming. However, the topic of touchscreen input was not the focus of that review, or of any survey work until now for that matter, despite touch and gesture input being the prevalent form of interaction on today's smart mobile devices.

This section surveys *touchscreen interactions* for mobile devices that, because of their reliance on visual stimuli, remain little accessible to mobile users with visual impairments of either pathological or situational nature. Such a focused review has not been conducted yet in the community, despite the wide prevalence of touch and gesture input for mobile devices. In this section, we adopt a survey methodology consisting in three steps (see Figure 3), and we discuss (a) studies that examined the *accessibility challenges* encountered by people with visual impairments when using mobile touchscreen devices and experimental findings regarding the *touch input performance of users with visual impairments on mobile devices*, (b) *interaction techniques* designed to make touchscreen devices more accessible to people with visual impairments, and (c) *mobile applications*, including commercial software. We also point to recent methodologies and tools for gesture analysis, such as (Anthony et al., 2013; Kane et al., 2011b; Vatavu et al., 2013, 2014; Vatavu and Wobbrock, 2015, 2016; Wobbrock et al., 2009), that have already started to be employed in the community to better understand gesture input on mobile touchscreen devices for people with visual impairments; see recent work by Buzzi et al. (2015, 2016). Overall, we survey 215 references that were published between 1972 and 2016 that are related to the object of our survey; see the figure on the right for year distributions of previous work.

We start this survey by examining the accessibility challenges encountered by people with visual impairments when interacting with smart mobile technology (Brady et al., 2013; Buzzi et al., 2015; Kane et al., 2008a; Buzzi et al., 2016; Kane et al., 2009, 2011b; Leonard et al., 2005; Shinohara and Tenenberg, 2007; Ye et al., 2014). Our main focus is touch and gesture input techniques, but we also discuss previous work examining other mobile accessibility problems and associated assistive techniques, when relevant. Therefore, we refer to previous work on the design and development of interaction techniques that exploit sensory substitution (Burch and Pawluk, 2009; Kane et al., 2013b; Landau and Wells, 2003; McGookin et al., 2008; Wall and Brewster, 2006; Xu et al., 2011); we discuss relevant software features that improve the accessibility of mobile devices overall, such as on-screen narration of text and visual content, gesture sonification, and audio and tactile feedback (Kane et al., 2013b; Landau and Wells, 2003; Oh et al., 2015; Wall and Brewster, 2006); and we reference commercial software, such as popular screen readers with considerable impact on the accessibility of mobile devices (Apple, 2016; Google, 2016b). The discussion that follows groups related work into three main chapters:

1. Observations from the literature on how mobile devices are used by people with visual impairments, including preferences for mobile devices, workaround strategies, and users' performance with touch gesture input.

2. Design of interaction techniques to improve the accessibility of touchscreen devices, such as techniques that exploit sensory substitution implemented with audio and haptic feedback, or techniques that improve touch and multi-touch input accuracy for people with visual impairments.

3. Applications of assistive input, including a discussion of commercial applications, such as screen readers, photo and video captioning, and navigation assistance apps.

We start this section with a brief discussion of the diseases of the eye as they are cataloged by the World Health Organization (WHO, 2016) and we present technical solutions designed to address specific causes of visual impairment, such as refractive errors or age-related macular degeneration.

2.1 Diseases of the eye: A brief overview

The World Health Organization lists 11 categories of diseases of the eye, according to its 10*th* revision of the International Statistical Classification of Diseases and Related Health Problems; see (WHO, 2016), chapter VII, "Diseases of the eye and adnexa." Visual impairments are listed under the "Visual disturbances and blindness" category and are classified into four main types, according to visual acuity; see (WHO, 2016);

1. *Mild* or no visual impairment (visual acuity is equal or better than 6/18). People with mild visual impairments can indicate signs of vision problems, but normal vision is easily attained with corrective lenses.

2. *Moderate* visual impairment (visual acuity equal or better than 6/60, but worse than 6/18). People in this category need low-power magnifiers or large fonts for reading. They can perform lucrative activities that do not require large dependence on visual stimuli.

3. *Severe* visual impairment (visual acuity equal or better than 3/60, but worse than 6/60). People with severe impairments experience problems in spatial orientation and accommodation problems to changes in light intensity. High-power magnifiers and vision amplifiers are needed.

4. *Blindness* (visual acuity worse than 3/60). Considerable difficulties need to be overcome for spatial orientation and assistance is needed. Information is obtained through audio and Braille books and devices.

According to (WHO, 2014), the major causes of visual impairments worldwide are uncorrected refractive errors, such as myopia, hyperopia, and astigmatism (43% incidence), unoperated cataract (33%), and glaucoma (2%). Age-related macular degeneration, trachoma, diabetic retinopathy, and corneal opacities follow at about 1%; see Figure 4. Also, a large proportion (18%) of causes leading to visual impairment is still undetermined (WHO, 2012). The most affected age group is represented by persons aged over 50 years old that account for 65% of all the population affected by some form of visual impairment (WHO, 2012), followed by the

15-49 years old group with 28% and children less than 14 years old with 7%.

Refractive errors are responsible for visual acuity loss. Depending on severity, loss in visual acuity affects accurate perception of the information displayed by the screen of a mobile device; see Figure 5, top row, for simulations. Unlike other diseases of the eye, refractive errors cannot be prevented, but they can be diagnosed and treated with corrective glasses, contact lenses, or refractive surgery. Vision disturbances caused by refractive errors have been addressed in the technical literature. For instance, Guerreiro et al. (2011) examined individual differences in the performance of people with visual impairments with a key acquisition task on the keypads of various form factors of mobile devices. Results revealed that spatial acuity significantly affects key acquisition performance, *e.g.*, people with less visual acuity take longer to locate keys on the keypad of the mobile device. Recent advances in augmented reality technology and wearables made possible vision enhancement systems, such as ForeSee or CueSee (Zhao et al., 2015, 2016) that present people with low vision with visually-enhanced views of the reality, such as magnifications, enhanced contrast and highlighted edges, or automatic detection of text and objects. Also, recent advances in display technology enable visualizations of on-screen objects tailored to the subject's focal length (Pamplona et al., 2012), freeing the viewer from the need of wearable optical corrections when looking at the display.

Age-related macular degeneration is a condition in which the macula (an oval area near the center of the retina, responsible for sharp central vision) suffered damages. The symptom is blurred area near the center of vision which, with time, grows larger. Figure 5 illustrates the AMD effect on the perceived image in the mild, moderate, and severe conditions. AMD interferes with the ability to see faces, read, write, or do close work. AMD has been addressed in the technical literature. For instance, Hakobyan et al. (2013, 2014) designed an accessible mobile app (diet diary) for people with AMD by adopting a participatory design approach. Leonard et al. (2005) examined factors that affect interaction performance with mobile devices of people affected by age-related macular degeneration (AMD). The AMD severity score and contrast sensitivity were found to predict the efficiency of user interaction in terms of content search, selection, and manipulation.

Diabetic retinopathy is caused by damage to the blood vessels in the retina, because of high blood sugar in diabetes. Bleeding retinal blood vessels determine the appearance of floating spots in the visual field. Figure 5 illustrates simulations of the diabetic retinopathy effect on the perceived image in the mild, moderate, and severe conditions. Diabetic retinopathy represents the most common cause of vision loss among people suffering from diabetes. Azrak et al. (2015) developed the Diabetic Retinopathy Predictor, a statistical predictor and mobile application for Android and iPhone that implements a binary logistic regression model to detect diabetic retinopathy or macular edema from objective variables, such as type of diabetes, gender, age, glycated hemoglobin (HbA1c), foveal thickness, and visual acuity (best corrected). Chhetri et al. (2010) introduced an iPhone implementation of the shape discrimination test for timely detection of proliferative diabetic retinopathy or diabetic macular edema, taking into consideration accessibility design guidelines, such as simplicity and visual clarity of the user interface for patients with eye conditions. Prasanna et al. (2013) introduced a smartphone app implementing a decision support system for initial screening of diabetic retinopathy that delivered an average sensitivity of 86%.

As mentioned above, 78% of all causes of visual impairments are determined by refractive errors, cataract, and glaucoma, while 18% are still undetermined. While some researchers have already started to focused on specific eye conditions (Hakobyan et al., 2014; Pamplona et al., 2012; Prasanna et al., 2013), more studies and examinations are needed as well as more design and development efforts to improve the accessibility of mobile devices for all visual abilities.

2.2. Mobile device use by people with visual impairments

Studies observing how people with visual impairments use mobile technology have revealed rich and useful information about their preferences for mobile devices, the importance of various features of mobile technology to improve accessibility and the actual importance of those features in the everyday lives of people with visual impairments, as well as the workarounds that people with visual impairments tend to develop for situations where current assistive technology fails (Shinohara and Tenenberg, 2007; Kane et al., 2008a, 2009; Szpiro et al., 2016a,b; Ye et al., 2014). Previous research has examined use trends, differences in how mobile technology is used by people with and without visual impairments, factors that affect interaction performance with mobile devices, users' touch input performance and users' gesture preferences and gesture production patterns on mobile touchscreen devices. The findings of these studies, put together, form a rich understanding of the accessibility challenges that people with visual impairments deal with when interacting with touchscreen devices. In this section, we group and discuss such discoveries reported by previous work.

2.2.1. Preferences for mobile devices

Several studies have reported on the types of mobile devices that people with visual impairments use and examined how those devices were being used. An interesting investigation of Shinohara and Tenenberg (2007) conducted under the name "observing Sara," presented the case of a blind person's interactions with technology, from which several recurring themes emerged, such as the importance of technology to not "mark" the user as blind, to support independence with portability and control, and to allow for brute-force alternatives in case of task failure which, by exhaustively trying all possibilities, can guarantee task completion. The technology biography of Sara could only account for mobile technologies available in the year 2007, such as tactile watches with Braille-like dots, screen readers with limited functionality, and simple mobile user interfaces, such as for rendering text messages on the phone. Since then, Ye et al. (2014) and Kane et al. (2009) examined other, more recent types of mobile devices that are now employed by people with visual impairments. Their investigations (in the form of interviews and on-line surveys) showed that people with visual impairments employ smartphones, music players, and GPS devices designed for generic users, but they also rely on their accessibility devices, such as canes, magnifiers, and Braille compasses; see (Kane et al., 2009). However, advances in mobile technology determined such accessibility devices to be progressively replaced with software screen readers, wired headphones, Bluetooth keyboards and headsets, refreshable Braille displays, and software screen magnifiers (Ye et al., 2014). Furthermore, recently available wearable devices, such as wristbands, augmented glasses, and rings that do not rely on visual input could have a positive impact on the ability of people with visual impairments to access information in mobile settings; see (Ye et al., 2014) that reported positive reactions from people with visual impairments to such eyes-free input wearables. Kuber et al. (2012) focused on the difficulties encountered by people who are blind when using screen reader technology on mobile devices and reported specific problems, such as limited functionality of screen readers, difficulties in accessing content discretely, limited feedback, and difficulties to understand speech output in loud and noisy environments.

2.2.2. Workaround input strategies for mobile devices

Previous work has reported workarounds that people with visual impairments tend to use on touchscreen devices when they encounter accessibility challenges regarding the ways mobile devices were designed to function, accept user input, and provide feedback and output (Kane et al., 2008a, 2009). Kane et al. (2008a) observed how people with visual impairments use mobile touchscreen technology and inventoried several workarounds to make mobile technology usable, such as attaching tactile dots or Braille labels directly to touchscreens, memorizing the locations of on-screen objects, asking other people for help or, when everything else fails, they simply avoid performing tasks that require a touchscreen. Informants from that study specifically pointed to the difficulty of learning object locations on the screen and expressed concerns about activating features accidentally with unintended touches that may result in unwanted consequences, such as deleting files. More accessibility problems and associated workaround strategies were revealed by Kane et al. (2009), who further examined the ways in which people with visual impairments use mobile devices in their daily lives. Accessibility and usability issues were reported by 20 participants with a range of abilities, including total blindness, low vision, but also motor impairments. Participants indicated various accessibility problems, such as on-screen text being too small or screen contrast too low for effective use. Situational factors with negative effect on mobile interaction performance also emerged, such as issues encountered when operating devices while navigating in crowded spaces, low screen readability in very bright or very dim light, or the fact that using devices during walking reduces people's situational awareness, making it difficult, for instance, to hear other sounds in the environment. Kane et al. (2009) also reported a variety of strategies that people with visual impairments employ in order to use mobile devices independently, such as resorting to device settings adjustments (*e.g.*, set bigger font sizes), installing and using screen reader software, using multiple devices to overcome accessibility problems, or making a practice of using the device at home with magnifiers to memorize locations of on-screen objects, such as buttons.

These specific findings regarding mobile technology connect to more general observations from the literature of the accessibility of technology for people with visual impairments. For instance, Brady et al. (2013) examined the visual challenges experienced by people who are blind in their everyday lives and reported results from a large scale study in which over 5000 participants asked over 40000 questions about photographs they took using a custom application, *e.g.*, "what color is this shirt?". A taxonomy of questions was produced consisting in identification questions (*e.g.*, "what is this?"), reading questions (*e.g.*, "what does this say?"), description questions (*e.g.*, "what color is this?"), and other questions that point to the many difficulties encountered by people who are blind and which could be addressed with assistive mobile technology; see (Brady et al., 2013) (p. 2120). Furthermore, Szpiro et al. (2016a) reported in a recent study that the needs of people with low vision for accessible technology differ from those of people who are blind, with implications showing the importance of designing technology for vision enhancement (Szpiro et al., 2016a,b; Zhao et al., 2015, 2016).

2.2.3. Touch gesture input for people with visual impairments

Studies on how people with visual impairments use touch gestures have been scarce and, consequently, there is little information today on the touch and gesture input performance of people with visual impairments, despite a large body of knowledge on touch input for people with full sight (Bacim et al., 2013; Chang et al., 2015; Holz and Baudisch, 2011; Lee and Zhai, 2009; Park and Han, 2014; Vatavu et al., 2015, 2013; Wobbrock et al., 2009; Tu et al., 2014). We discuss in this section previous results on gesture preference and gesture input performance for users who are blind (Buzzi et al., 2015, 2016; Kane et al., 2011b) and we also point to existing techniques and methodologies from the gesture literature that could be employed to conduct more such studies towards a better understanding of how people with visual impairments articulate gestures on touchscreens. In the following, we discuss previous work on the *gesture preferences* and the *gesture articulation performance* of people with visual impairments.

The first study that looked at touch gestures produced by people with visual impairments was (Kane et al., 2011b), who examined preferences for gestures on mobile devices in the context of a gesture elicitation study, where gesture commands invented by 10 participants were compared to gestures proposed by 10 people with full sight. Findings revealed that people who were blind used more strokes per gesture, invented more edge and corner gestures, and made use more frequently of mode changers to reduce potential conflicts between gestures, *e.g.*, an extra touch precedes the actual gesture command for multi-touch input. More gesture preferences were revealed by Buzzi et al. (2015, 2016), who reported preferences for round-shaped gestures, one-finger input, one-stroke gestures, and short gesture trajectories. These results indicate the importance of simple and efficient designs of gesture shapes (Kane et al., 2011b; Buzzi et al., 2015), the need for physical anchors to start and/or end a gesture command (Kane et al., 2011b), and also the need for specific interaction techniques, e.g., mode and also the need for specific interaction techniques, *e.g.*, mode switchers, to assist gesture input on touchscreens (Kane et al., 2011b). These studies implemented the gesture elicitation methodology, which represents an effective technique to reveal discoveries about users' gesture preferences to inform gesture set design. Introduced by Wobbrock et al. (2005) to maximize the guessability of symbolic input and first applied to touchscreen gestures by by Wobbrock et al. (2009), the elicitation methodology has now a rich set of measures of agreement and coagreement of participants' preferences, associated statistical tests, and a public software tool (AGATe) to assist such investigations; see Vatavu and Wobbrock (2015, 2016).

Knowing what gestures people prefer to perform to effect specific tasks is important knowledge to inform the design of gesture sets for specific applications. However, how those gestures are actually articulated and how much they vary from one execution to the next can impact the performance of gesture recognizers. For instance, Kane et al. (2011b) found that the recognition accuracy for symbolic and shape gesture types reached maximum values of 44.9% and 78.7%, respectively, depending on the structure of the training set; see (Kane et al., 2011b) for results (p. 420) and Anthony and Wobbrock (2010) for the gesture recognizer employed in that work. To improve accuracy, detailed information is needed about how people with visual impairments produce gestures compared to people without impairments, for which popular recognizers like the ones in (Anthony and Wobbrock, 2010; Wobbrock et al., 2007; Vatavu et al., 2012) are able to deliver 99% accuracy rates.

Kane et al. (2011b) also examined differences in touch gesture articulation performance between people with and without visual impairments for a large set of gesture types including taps, directional flicks, shapes, and symbols. Results showed that gestures produced by people who were blind were larger in size, wider, had greater size variation, and were produced at slower speeds than gestures articulated by participants with full sight. In a recent study, Buzzi et al. (2016) examined gesture articulation using more recent gesture techniques, such as the analysis of gesture consistency and the relative accuracy of gestures using the GECKo and GREAT toolkits of Anthony et al. (2013) and Vatavu et al. (2013). Results revealed articulation differences between gestures produced by people who were blind and people with low-vision in terms of Stroke Ordering Error (SkOE), Bending Error (BE), and Speed Error (SE) accuracy measures; see Vatavu et al. (2013) for a definition of these measures as well as for other gesture relative accuracy measures. In particular, gestures produced by people who were blind had lower Stroke Ordering Errors than gestures produced by people with low vision, showing a larger tendency of people who were blind to reproduce their gesture strokes consistently from one articulation to the next than it was the case for people with low vision. Results also showed that people who were blind were less consistent with multi-stroke gestures and that they had difficulties with gestures with steep or right angles. Unfortunately, Buzzi et al. (2016) did not compare gestures produced by people with visual impairments against gestures of people with full sight. Therefore, more work is needed to understand the performance of gesture input of people with visual impairments using the newest gesture analysis methodologies available today (Anthony et al., 2013; Vatavu et al., 2013). Furthermore, other gesture tools have been made available recently, such as visualization techniques that use color coding to point to variations in gesture articulation, known as "gesture heatmaps", which can further reveal important differences between gestures produced by people with and without visual impairments; see the GHoST toolkit of Vatavu et al. (2014). Comparisons with other mobile scenarios, such as situationally-induced visual impairments, are also needed, because even sighted people articulate gestures differently when they lack visual feedback; see, for instance, Tinwala and MacKenzie (2010) for eyes-free text entry on touchscreen mobile devices.

2.3. Interaction techniques to improve touchscreen accessibility for people with visual impairments

The accessibility literature includes a large variety of interaction techniques designed for people with visual impairments to use mobile devices more effectively when performing specific tasks, *e.g.*, generic text entry (Frey et al., 2011; Guerreiro et al., 2008; Oliveira et al., 2011), or for specific applications, such as navigation assistance (Bischof et al., 2012; Buzzi et al., 2011; Frey et al., 2011; Guerreiro et al., 2008; Oliveira et al., 2011; Pressl and Wieser, 2006). Previous work on interaction techniques for accessible mobile devices can be grouped by many criteria, such as *application type* (*e.g.*, navigation, communications, assistance with objects identification, etc.), *input and output modalities* (*e.g.*, audio, tactile, assistive techniques to improve accessibly of photos and videos), *device type* (*e.g.*, mobile, wearable, glasses, touch-sensitive screens) or *interface type* (*e.g.*, touchscreen, motion gesture, voice input, etc.). Kane et al. (2011b) employed a classification of interaction techniques for assistive touch user interfaces that grouped previous work in techniques for *menu browsing*, *discrete gestures*, and techniques that used *fixed regions* on the screen. In menu browsing, the user goes through a list of options, which are rendered with speech output; see (Kane et al., 2008a; Guerreiro et al., 2008; Apple, 2016; Project-RAY, 2016). Discrete gestures allow users to execute specific actions that were previously mapped to those gestures, for example as demonstrated by McGookin et al. (2008). Fixed regions map specific areas of the screen to predefined functions, such as the 9-key virtual keyboard design of the Mobile Messenger for the Blind system of Sánchez and Aguayo (2007). In the following, we adopt a simple taxonomy to group previous work on interaction techniques for mobile touchscreen accessibility, which we discuss from the perspective of (a) *output techniques* implementing audio and tactile feedback to assist perception of on-screen visual content and (b) *input techniques* for entering text, performing selections, and effecting generic commands.

2.3.1. Tactile and audio feedback delivery techniques for people with visual impairments

Research on the accessibility of mobile touchscreen interaction has explored the principle of "sensory substitution" (Burch and Pawluk, 2009; Kane et al., 2013b; Landau andWells, 2003; McGookin et al., 2008; Wall and Brewster, 2006; Xu et al., 2011) and, consequently, employed tactile and audio feedback to render visual information in non-visual ways in order to help people with visual impairments to better understand and control on-screen visual content (Frey et al., 2011; Kim et al., 2013; Guerreiro et al., 2008; Kane et al., 2008a).

Previous work on haptic feedback techniques has focused on new technology to deliver tactile cues (Xu et al., 2011) or on creative use of tactile layers superimposed on touchscreens

(Kane et al., 2013b; McGookin et al., 2008; Wall and Brewster, 2006). For instance, Xu et al. (2011) introduced "TeslaTouch," a technology to deliver haptic feedback to users' fingers while fingers move on the surface of the touchscreen. TeslaTouch renders representations of 2-D information to people with visual impairments by modulating the friction force felt by the moving finger in response to a voltage difference applied between the finger and a conductive layer installed on the touchscreen. Applications enabled by TeslaTouch include rendering Braille letters, tactile cues to help identifying on-screen images, and tactile-assisted drawing. Another example of new technology for tactile feedback is (Burch and Pawluk, 2009), who developed a finger-worn device consisting of an RGB sensor and a piezoelectric actuator that rendered the color emitted by the screen into vibration signals that simulate texture on the tip of the user's finger. Qian et al. (2013) introduced "tactile icons" to support users in situational impairments, and found that people prefer vibrotactile feedback that has a simple structure. For example, vibrotactile intensity can be mapped to message urgency, while feedback duration to message length. The HaptiMap project investigated ways in which multimodal feedback can enhance and/or replace visual feedback (Giachritsis et al., 2012; HaptiMap; Pielot et al., 2012; Szymczak et al., 2012). Toward this goal, Giachritsis et al. (2012) introduced a technique to design intuitive navigation patterns for users by employing vibrotactile signals to encode directions, landmarks, and actions required for navigation. Mobile devices were employed by Szymczak et al. (2012) to provide navigation guidance by delivering meaningful vibrotactile messages to point users into the desired direction, *e.g.*, more frequent vibrations were delivered when users were getting closer to their goal. Addressing mobile navigation in demanding conditions, Pielot et al. (2012) proposed "Tacticycle," a user interface for a bicycle navigation system that helps users orient themselves while cycling. Recently, Schönauer et al. (2015) evaluated users' ability to recognize vibrotactile feedback of various intensities and durations delivered at arm level during gesture articulation, but they only evaluated the performance of people with full sight. More work is needed to understand vibrotactile perception during gesture articulation for people with visual impairments.

Many researchers focused on using tactile overlays superimposed on touchscreens to provide haptic guidance for people with visual impairments. For instance, McGookin et al. (2008) implemented a touchscreen overlay for mobile devices in the form of a raised paper control panel with tactile buttons, which was demonstrated to control an MP3 player application. Performance evaluation results showed that users were significantly faster with the overlay than when using touch gestures alone. Wall and Brewster (2006) introduced "tac-tiles," an interface that enables users with visual impairments to explore on-screen graphics using both tactile and audio feedback. Tac-tiles were implemented on a graphics tablet by using an overlay tile with physical relief to guide exploration and help users quickly orient themselves within the on-screen visualization. Graphical content was explored with a stylus guided by the relief of the overlay, while a tactile pin-array was used to deliver haptic feedback on the fingertips of the non-dominant hand. Landau andWells (2003) introduced the Tactile Touch Tablet for haptic output delivered through a set of custom tactile sheets, such as a sheet in the form of a map (p. 415), while audio data was rendered when users pressed the tactile drawing. Kane et al. (2013b) extended these techniques for generic touchscreen interfaces and introduced "touchplates," which are tactile overlays that deliver haptic feedback to people with visual impairments when interacting with standard touch interfaces. Touchplates are inexpensive to manufacture (*e.g.*, they can be made out of cardboard) and are customizable to accommodate a variety of tactile landmarks (*e.g.*, holes, edges, or rigged areas). Touchplates can support a large palette of interactions, such as text entry, working with windows and menus, and even exploring 2-D data with elaborate overlay designs, such as map cutouts; see (Kane et al., 2013b) (p. 22:4).

2.3.2. Touch and gesture interaction techniques on mobile devices for people with visual impairments

A lot of efforts have been conducted to design assistive input techniques for people with visual impairments to enter text, perform selections, and execute commands effectively on mobile touchscreen devices. These techniques have either adapted existing Braille input and output designs for mobile devices (Frey et al., 2011; Oliveira et al., 2011; Guerreiro et al., 2008) or implemented novel screen-reader technology to assist generic gesture input on mobile devices (Kane et al., 2008a, 2013a).

A specific class of text entry techniques designed for people who are blind rely on Braille-type input for touchscreen devices. For instance, Frey et al. (2011) introduced "BrailleTouch," a soft keyboard designed for eyes-free text entry, which consists of six soft buttons with direct correspondence to the six parts of a Braille character. Another text-entry technique based on the Braille alphabet is "BrailleType" that uses dot characters entered with finger taps in six locations on the screen (Oliveira et al., 2011). Azenkot et al. (2012b) introduced IFD, the Input Finger Detection technique, that was applied to the Perkinput text entry method to deliver significantly faster and more accurate text entry on mobile devices than when using VoiceOver. We refer the reader to Siqueira et al. (2016) for a review on Braille-inspired text entry techniques for smartphones. Other approaches for entering text explored various keyboard designs, search-based techniques to locate letters in the alphabet, or mappings between multi-touch gestures and letters. For example, Sánchez and Aguayo (2007) employed a 9-button software keyboard and text-to-speech technology to enable users who are blind to operate an instant messenger application on mobile devices and Guerreiro et al. (2008) employed directional gestures to navigate through a list with the letters of the alphabet.

Another direction of work has looked at improving the accessibility of generic multi-touch input with various techniques. For example, Kane et al. (2008a) introduced "Slide Rule," a set of multi-touch techniques that render the content of a visual touch interface using audio feedback, *e.g.*, Slide Rule speaks the first and last name of a contact in the phone book when the user's finger touches the corresponding area on the screen. Slide Rule enables both content understanding and command execution: a one-finger scan browses lists, a second finger tap selects on-screen items, multi-directional flicks perform actions, while an "L"-shaped stroke gesture is used to access hierarchical information. "AccessLens" (Kane et al., 2013a) is another interaction technique that employs computer vision-based hand tracking to enable people who are blind to use gestures on paper documents and other physical objects, such as product packages, screens, and home appliances. Azenkot et al. (2012a) developed "PassChords," a secure multi-touch authentication technique that employs consecutive taps performed with one or more fingers to enter passwords on touch-screen devices. Vertanen (2016) used a finger counting technique to map the number of fingers and the relative locations of their touches to the letters of the alphabet. Finally, "DigiTaps" is an eyes-free number entry technique that uses combinations of taps and swipes performed with one, two, or three fingers to specify digits from 0 to 9

(Azenkot et al., 2013). All these techniques were designed to improve the accessibility of multi-touch input for mobile devices for people with visual impairments by using smart ways to infer grasps and fingers touching the screen, intended targets, and how users touch those targets on the screen.

As touchscreen interactions rely on touch and gesture input, researchers have also looked at ways to teach the gesture set of an application to users with visual impairments. Although many techniques exist for people without visual impairments, such as OctoPocus (Bau and Mackay, 2008; Delamare et al., 2016) or crib-sheet diagrams (Kurtenbach et al., 1994), these techniques rely on visual stimuli to help memory recall and, therefore, are not applicable to people who are blind and have limited applicability to people with low-vision, *e.g.*, OctoPocus (Bau and Mackay, 2008) may create "visual clutter" if too many suggestions for gestures are presented to the user simultaneously. To address this problem, Oh et al. (2015) introduced gesture sonification (*i.e.*, finger touches produce sounds, which create an audio representation of a gesture shape) and corrective verbal feedback (*i.e.*, speech feedback provided by analyzing the characteristics of the produced gesture). Another work (Oh and Findlater, 2015) examined on-body versus touchscreen gesture input for people with visual impairments, such as pointing and shape gestures, and showed the potential of on-body input for accessible non-visual mobile computing.

Findings from these studies were used to compile design guidelines for mobile touch user interfaces for people with visual impairments. For example, based on experimental evidence, McGookin et al. (2008) formulated specific recommendations for implementing touchscreen accessibility, such as avoid short impact gestures, such as a tap, because of accuracy concerns and accidental target invocation; provide a discernible tactile "home" location; and provide feedback, such as audio, for all interactions involving a touchscreen. Kane et al. (2009) also drew several guidelines for making mobile devices more accessible and empowering, such as provide increased configurability and interaction adaptation to environmental factors. Kane et al. (2011b) recommended gesture user interface designers to favor edges, corners, and other landmarks on the touchscreen device, reduce demand for location accuracy, and avoid symbols used in print writing, because people who are blind may have limited knowledge with them.

2.4. Mobile applications for people with visual impairments

Mobile application development for users with visual impairments has focused mostly on assisting orientation and navigation, both indoor (Chen et al., 2012; Poláček et al., 2012) and outdoor (Pressl and Wieser, 2006) and to help people travel in public transportation (Bischof et al., 2012). Other application areas include assisting everyday life activities, such as matching color and texture of clothes (Tian and Yuan, 2010), helping in business negotiations (Karim et al., 2006), making visual maps accessible (Buzzi et al., 2011), and even performing challenging tasks, such as controlling a flying helicopter (Minatani and Watanabe, 2012). Bigham et al. (2010) and Schauerte et al. (2012) implemented computer vision techniques to detect objects and help people who are blind to find lost things. "KnowWhat" is a prototype that uses a video camera to decode fiducial markers placed in the environment (Pareddy et al., 2016). Azenkot et al. (2011) developed "MoBraille" (*i.e.*, mobile Braille), a framework that connects an Android device to a Braille display over HTTP and enables people who are blind to access information in Braille from mainstream smartphone devices.

Researchers have also explored new designs for mobile devices, specifically tailored for users with visual impairments. For example, Quek and Oliveira (2013) designed a haptic glove interface to enable individuals with blindness or severe vision impairments with awareness of the deictic gestures performed by an instructor. Gollner et al. (2012) introduced a new glove design to support communication for people who are deaf and blind: the device translates the hand-touch alphabet Lorm, used by people with both hearing and sight impairments, into text and vice versa. Shaik et al. (2010) showed how the existing design of a mobile device (an Android mobile phone) can be re-configured for easier usage by people with visual impairments.

Several commercial technologies are available today for Android and iOS mobile devices to improve the accessibility of mobile user interfaces for people with visual impairments. Screen readers, such as VoiceOver and Google TalkBack (Apple, 2016; Google, 2016b), come preinstalled and, probably, represent the most prevalent form of assistive technology for today's mobile touchscreen devices for people with visual impairments. VoiceOver enables users with instant access to audio descriptions of on-screen content triggered by means of touch gestures, *e.g.*, a simple tap plays the description of a button, while a double-tap executes the function associated to that button (Apple, 2016). Android's accessibility features available to app developers include the preinstalled TalkBack screen reader that renders the results of an action with spoken feedback, the "explore by touch" system that reads content found at the location of the user's finger touching the screen, and access to system settings to adjust display and sound options for improved accessibility for a range of visual abilities; see Google (2016a).

Recent efforts were devoted to improve photos and video accessibility for the web and, especially, for visual content delivered on Social Networking Services. For instance, Twitter has introduced photo captioning in 2016 to describe visual content to users with visual impairments in the form of alternative text up to 420 characters (Larson, 2016b). Yahoo has started to provide close captioning for some of their featured videos (Larson, 2016a). Providing alternative text to visual content is important, as revealed by recent studies showing that people with visual impairments participate on Facebook as much as the general population (Wu and Adamic, 2014), yet they experience accessibility challenges because of the large prevalence of photos and videos without sufficient text description (Voykinska et al., 2016). More advanced screen readers have started to take advantage of recent developments in visual object recognition from static images to provide automatic alternative text in order to make on-screen visual content more accessible to people with visual impairments. For instance, Facebook's Moments app can already recognize about 100 distinct concepts in photos, besides peoples' faces, such as people's appearance (*e.g.*, eyeglasses, beard, smiling), nature (*e.g.*, mountain, snow), transportation (car, airplane, bicycle), sports (tennis, swimming), and food (*e.g.*, ice cream, pizza, dessert, coffee). This technology enables *"people using a screen reader to access Facebook on an iOS device [to] hear a list of items that may be shown in a photo"* (Garcia et al., 2016), improving the accessibility of photos for the web and Social Networking Sites.

A few recent projects on mobile computing and mobile apps have launched an entire series of hardware and software products that offer multiple functionality to people who are blind or with low vision. For instance, RAY devices and apps were specifically designed for people with visual impairments to connect, communicate, and socialize; see (Project-RAY, 2016). The RAY App for Android devices exposes a simple eyes-free user interface, operable with one hand only, that replaces taps with directional swipes in the form of a simple marking menu (Zhao and Balakrishnan, 2004; Kurtenbach and Buxton, 1994) with audio feedback. Special designs of smartphones for people with visual impairments (*e.g.*, the RAY L5 or RAY N5) run a dedicated operating system and expose useful features, such as remote assistance for users to receive support over the Internet from their family members, navigation assistance, and visual identification apps that help with color or currency identification. Another family of assistive apps is "GeorgiePhone," which provides assistance for people who are blind or have low vision for various tasks, such as color identification, reading documents with optical character recognition, providing directions and assisting navigation (GeorgiePhone, 2016). Other commercially-available apps for Android and iOS devices help their users with vision enhancement tools to improve the visual perception of on-screen content via software magnification (AppdLab, 2016; SmartTools, 2016), map live camera views to audio feedback, such as soundscapes (Meijer, 2016), and provide navigation assistance and services for personal security (Shen, 2016).

2.5. Mobile technology for people with low vision

The term “visual impairments” includes a broad range of visual abilities, from moderate to severe impairments and blindness. However, unlike people who are blind, people with low vision do rely on their visual abilities to perform everyday tasks. Although work from as early as 1998 remarked people with low vision as an overlooked user group (Jacko and Sears, 1998), only recently studies have emerged to help designers and practitioners to understand accessibility challenges faced by people with low vision; see Szpiro et al. (2016b,a). For example, a very recent study revealed that the needs of people with low vision in terms of accessible technology differ from those of people who are blind (*e.g.*, people with low vision prefer accessing information visually than aurally) and outlined the need of high-performing vision enhancement tools (Szpiro et al., 2016a). Kim et al. (2013) examined haptic feedback for people with low vision and argued for specific designs to contrast design that targets people who are blind.

There are many causes for low vision and many ways in which vision disturbances manifest, *e.g.*, as blurred vision, faded colors or glare, blind spots in the visual field, color blindness, etc. In the following, we focus on mobile technology for enhancing vision for people with visual impairments, which has traditionally relied on software magnification approaches, now available commercially (AppdLab, 2016; Smart-Tools, 2016) or on interaction techniques that help acquire small targets; see (Appert et al., 2010; Grossman and Balakrishnan, 2005; Mott and Wobbrock, 2014). Recently, advances in head-mounted displays, augmented reality, and wearable technology have made possible new accessibility apps for people with low vision. An example is the “ForeSee” system of system of Zhao et al. (2015) that uses a video camera and an

Oculus Rift headset to render processed versions of the visual reality, such as magnifications, enhanced contrast and highlighted edges, or detection and recognition of text. A similar, yet less complex system comes from Hwang and Peli (2014), who implemented an edge enhancement visualization for Google Glass. "Chroma" is an augmented-reality system implemented with Google Glass that enables people with low vision to see an enhanced version of the visual reality according to their type of color blindness (Tanuwidjaja et al., 2014). "CueSee" is another example of an augmented reality system that assists product search by automatically detecting and highlighting the product on the head-mounted display (Zhao et al., 2016). New wearable technology and augmented reality software will likely have an important impact on enhancing visual abilities for people with low vision, helping them overcome accessibility problems on mobile touchscreen devices. However, more explorations are still needed to understand what, how, and when to improve and how these techniques can be tailored to specific visual abilities.

2.6. Situational visual impairments

The previous sections overviewed techniques designed to overcome the effects of *pathological* causes of visual impairment on mobile touchscreen interaction. However, visual impairment can also be *situational*, where the specific interaction context prevents a clear, direct view of the visual stimulus shown on the screen. Figure 2 illustrates some of these situations for mobile devices, such as partial and complete screen occlusion, difficulty to look at or to reach the mobile device, or screen glare. Although such situations can be easily corrected, they make touchscreen interactions with mobile devices temporarily not available for people without visual impairments of pathological cause. Some eye disorders, such as retina errors, can be treated with corrective glasses or surgery, but others do not currently have a cure, such as diabetic retinopathy, for which present-day therapy tries to prevent further vision loss. However, situational causes can be addressed and corrected with simple actions in the vast majority of cases (*e.g.*, by simply removing the object causing occlusion or adjusting the orientation of the device to reduce the effect of sun glare; see Figure 2); nevertheless, they pose difficulties for the correct perception of the visual stimulus. For mobile touch interactions, it may be that situational impairments are as problematic, for short periods of time, as visual impairments with a pathological cause (Wobbrock, 2006).

Sears et al. (2003) and Barnard et al. (2007) discussed *situationally-induced impairment and disabilities* (SIID) in the context of ubiquitous computing, determined by often changes in interactive scenarios experienced by users. The authors adopted a three-dimensional model to discuss the characteristics of SIID, employing the concepts of *human*, *environment*, and *applications*, by relying on the model of (Schmidt et al., 1999) used to describe "context." In the context of inclusive design, Elton and Nicolle (2010) and Nicolle and Elton (2016) identified the *person*, *nature of the task*, *physical environment*, and *social environment* as important for the context of use of a given product.

Previous work has investigated users' touch input performance on mobile devices under various situational impairments, such as walking or encumbrance (Abdolrahmani et al., 2016; Kane et al., 2008b; Schildbach and Rukzio, 2010; Ng and Brewster, 2013; Ng et al., 2013). For instance, Schildbach and Rukzio (2010) investigated users' selection and reading performance on mobile devices when walking and showed decreased performance (*i.e.*, 30% more time to select targets with touches that are 23% less accurate) and also an increase of cognitive load for walking compared to the standing condition. Compensatory approaches proposed and evaluated in that work consisted in increasing target sizes up to 40%. Ng and Brewster (2013) and Ng et al. (2013) evaluated the effect of encumbrance (*i.e.*, holding objects while using mobile devices) on target acquisition. Results showed that encumbrance and mobility decreased the performance of target acquisition, and also that encumbrance affected the dominant hand more than the non-dominant hand. Kane et al. (2008b) evaluated the feasibility of user interfaces for mobile devices that adapt layout when the user is walking. They identified the following key situational factors for walking user interfaces: walking path, walking speed, walking task, distractions, interruptions, location, obstacle, and hands, each with multiple choices: *e.g.*, sound, light level, and conversation represent potential distractors. However, all these studies evaluated the touch input performance of people *without* visual impairments. In contrast, Abdolrahmani et al. (2016) focused on situationally-induced impairments and disabilities *for* people who are blind, and exposed several challenges faced during mobile interaction when other accessibility devices, such as canes, need to be used as well. Results of Abdolrahmani et al. (2016) were compiled into a set of design recommendations for making mobile devices more universally and equally accessible no matter the situation, environment, or context. We relate to these recommendations in a specific section at the end of this paper.

A few techniques have been proposed in the literature to assist interaction for situationally-inducing impairments. For instance, "SwitchBack" is a system that employs gaze tracking to detect when users divert their attention from the mobile device and, when users revert back, it highlights where they were last looking (Mariakakis et al., 2015). Another example is adapting text entry on mobile devices according to the hand posture used to type text, *e.g.*, left thumb, right thumb, index finger, or two thumbs (Azenkot and Zhai, 2012; Goel et al., 2013; Wolf and Henze, 2014) for examples. “ContextType” and “WalkType” are examples of adaptive text entry systems for situationally-induced impairments (Goel et al., 2013, 2012a). However, more focused context detection techniques and context studies (Exler et al., 2016; Karikoski and Soikkeli, 2013; Wiese et al., 2013) are still needed to advance current knowledge to deal efficiently with situationally-induced impairments and disabilities.

A schematic view of the taxonomy of factors affecting visual perception that are responsible for pathological and situational impairments. Users, devices, and environments (physical and social) represent the main dimensions of the taxonomy.

The difficulty of perceiving visual content accurately on the device makes people with visual impairments to adopt workaround strategies, such as adjustments of the position and orientation of the device and/or body postures (a, b, c); in contrast, a person with full sight adopts a relaxed posture (d).

2.7. Summary

Previous work on mobile touchscreen interaction for people with visual impairments has looked at the accessibility challenges that visual impairments pose on effective touch and gesture interaction and addressed these challenges by proposing assistive techniques for a variety of mobile applications. The studies from the literature reported repeatedly that people with visual impairments employ strategies and workarounds to be able to use mobile devices effectively and independently. We also know that differences exist between people with and without visual impairments in terms of touch and gesture input and, consequently, there is the need for specific touch and gesture input design for a range of visual abilities. However, despite the existing large body of work on visual impairments and mobile touchscreen interaction, an overview of *causes of visual impairment* has not been conducted so far. However, such an overview, examining both *pathological* and *situational* factors, would help systematize knowledge in this area as well as to inform future research directions. In the following, we compile the first version of a catalogue of factors responsible for visual impairment in relation to mobile devices, and we present a taxonomy grouping these factors on three dimensions: users, devices, and environments. But first, we take a brief look at the pathology of the eye and report on the eye conditions with the highest incidence worldwide.

3. CATALOGUE OF FACTORS CAUSING VISUAL IMPAIRMENT FOR MOBILE DEVICES

This section introduces a taxonomy of factors responsible for visual impairment that can affect the effectiveness and/or efficiency of touchscreen interaction on mobile devices. The taxonomy was informed by pathological causes of visual impairment (see the previous section), by previous work on situational impairments (Abdolrahmani et al., 2016; Barnard et al., 2007; Sears et al., 2003), observations from the studies in the literature (Kane et al., 2008a, 2009; Ye et al., 2014; Shinohara and Tenenberg, 2007), previous work on inclusive design (Elton and Nicolle, 2010; Nicolle and Elton, 2016), and personal observations. The taxonomy is organized around four main concepts: (1) users, (2) devices, (3) the physical environment, and (4) the social environment; see Figure 6 for an overview. The purpose of this taxonomy is to better understand causes of visual impairment by cataloging them into relevant clusters.

3.1. The user dimension: pathological and psychological causes of visual impairment

The User category includes pathological and psychological factors that determine a user's capability to interact effectively with mobile devices and to perceive accurately visual content displayed on such devices. We identify the following factors pertaining to the user that are responsible for causing visual impairment:

1. *Pathological factors* cause disorders of the eye, which prevent formation of a correct visual perception and understanding of the visual stimulus. The visual function may be affected in many ways, such as central field loss, peripheral vision loss, color or contrast perception loss, or visual acuity loss (see the previous section for an overview of disorders of the eye and Figure 5 for visual illustrations). If some disorders of the eye can be corrected, such as refractive errors, others cannot. To compensate the difficulty of perceiving content clearly on the device, people with visual impairments adopt workaround strategies, such as adjustments of the position and orientation of the device or adjustments in body posture. To illustrate such outcomes, we performed observations with three persons with various visual abilities. Figure 7 shows a few snapshots captured from three persons with visual impairments that were asked to perform touch and gesture input on a tablet, such as drawing shapes and touching targets at random locations on the screen. Person P_1 (female, 33 years old) had chorioretinal degeneration (central vision affected); P_2 (male, 43 years old) had severe myopia (–11.0 diopters in both eyes) and congenital

nystagmus (involuntary, rhythmic eye movements); P_3 (female, 36 years old) had amblyopia (an eye fails to achieve normal visual acuity, even with prescription eyeglasses) in a severe condition (–6.00 diopters in both eyes). To cope with the task, everyone adopted specific body postures to compensate for their vision deficiency, which is one instance of workaround strategies that were observed in the literature (Shinohara and Tenenberg, 2007; Kane et al., 2008a, 2009; Szpiro et al., 2016a,b; Ye et al., 2014). In contrast, Figure 7d shows the more relaxed body posture of a person with full sight performing the same tasks.

2. *Psychological factors* may cause an inefficient distribution of the user's visual attention to the task on the device. The effect is that some visual stimuli will not be perceived correctly or will not even be perceived at all. Examples include overloaded visual attention because of multiple visual stimuli (Vatavu and Mancas, 2014, 2015), priorities in handling tasks (*e.g.*, while a high priority task, such as driving or jogging, is in progress, switching attention to the mobile device can lead to potentially dangerous outcomes), or dealing with visual distortions and optical illusions that deceive the eye (Khademi et al., 2012). Visual attention has been described and analyzed using the spotlight and zoom-lens models (Eriksen and Ho_man, 1972; Eriksen and James, 1986). The spotlight model (Eriksen and Hoffman, 1972) characterizes visual attention using focus (*i.e.*, the region from which information is extracted and processed at high resolution), fringe (*i.e.*, the low-resolution extraction of information at the boundaries of the focus region), and margin (*i.e.*, the cut-off of the visual attention area). The zoom-lens model (Eriksen and James, 1986) is an upgrade of the spotlight model, explaining the trade-off in the efficiency of the visual information processor: larger the focus, slower the processing. Inattentional blindness (or perceptual blindness) also falls into this category. Inattentional

blindness is a psychological phenomenon caused by the lack of attention without any vision defects, *i.e.*, an unexpected visual stimulus is not recognized, even when in plain sight (Mack and Rock, 1998; Rock et al., 1992): *"objects not attended to are not seen"* (Mack et al., 2002). Rock (1997) even argued that perception is an indirect process and that visual experience is derived by inference.

There are cases in which pathological factors determine psychological ones, while psychological factors may have physiological manifestations. For instance, a common psychological disorder associated to vision loss is depression. Rovner et al. (2007) found that patients with age-related macular degeneration are likely to experience depression within the next months after their second eye became affected. Senra et al. (2015) found that irreversible vision loss often has negative effects on the quality of life and mental health, while such effects tend to remain over time. Appollonio et al. (1996) noted an association between uncorrected sensory deprivation and a low quality of life for elderly people. People tend to develop anxieties caused by vision loss (Kempen and Zijlstra, 2014) and Ash et al. (1978) found that non-acceptance of blindness was associated with psychological distress and low social adjustment. Moschos (2014) described further connections between the physiology and psychology of vision disorders.

3.2. The device dimension: technical characteristics that affect visual perception

The Device dimension refers to all the aspects that characterize the capability of a given device to deliver clear, undistorted visual stimuli to its users. The technical characteristics of a device may lead to correct, partially correct, or even incorrect perceptions of visual content displayed by that device. Differences in product design, parts, production costs, and manufacturing processes will determine differences in product quality, with direct effects on the perception of on-screen content, such as the perception of colors or fine details of high-resolution graphical content. The following factors were catalogued under the Device category:

1. *Hardware capability* represents the technical characteristics of the device's screen, such as pixel resolution, dpi, and brightness. While smart phones and tablets have reasonably large screen sizes, smartwatches usually come with very small screens, *e.g.*, the Samsung Galaxy Gear S has a 50.9mm diagonal, while the Gear Fit's total dimensions are just 23.4 × 57.4mm. Other wearable displays, such as fingernail displays (Su et al., 2013; Wimmer and Echtler, 2013), are even much smaller. Screen quality, such as resolution, brightness, or technology, may affect perception of fine visual details. Also, because the screen represents the principal cause of battery consumption on mobile devices, a low battery level will force the operating system to save energy and, consequently, to reduce the brightness of the screen, affecting overall perception of displayed content. In fact, Schuchhardt et al. (2015) observed that current adaptive display brightness schemes are not well-tuned to user preferences.

2. *User interface design* represents all the elements that compose the interface presented to the user. Examples that limit accessibility are text too small to be easily read, little contrast between text and background, and a poor choice of colors. User interfaces tailored for the individual are needed in such situations. For example, Supple is a system that can automatically generate personalized user interfaces (Gajos andWeld, 2004; Gajos et al., 2010), which was demonstrated for people with visual impairments (Gajos et al., 2007) (Supple++) in the context

of ability-based design (Wobbrock et al., 2011).

3. *Occlusion of content*. Selection of on-screen content on mobile devices involves finger touches and, consequently, part of the screen gets occluded by the user's fingers, hand, or arm. Fortunately, occlusion models exist for tablets and interactive tabletops (Vogel et al., 2009; Vogel and Casiez, 2012) in the context of designing occlusion-aware interfaces (Vogel and Balakrishnan, 2010). These models can be used to display content dynamically on the screen, compensating for finger and hand occlusions.

4. *Device accessibility* may be sometimes limited because of the impossibility to reach the device or to look at its screen directly. For instance, hands may be busy (*e.g.*, carrying objects; see Figures 2c,d) or the user may be involved in an activity that cannot be interrupted (*e.g.*, driving, jogging, etc.). The smartphone placed face down during a meeting or placed at the ear during a conversation does not allow content to be visualized. The device may be covered by other objects or may be difficult to reach (*e.g.*, while in the pocket or inside a bag). Some work focused on making smartphones more aware of their context of use and, therefore, more accessible to people with visual impairments (Li et al., 2010) through innovatory techniques such as "phoneprioception" (Wiese et al., 2013).

3.3. The physical environment

This category includes all the physical aspects, exterior to the device and the user, that nevertheless affect interaction between the user and the mobile device. We identified the following factors responsible for causing conditions of visual impairment in relation to the physical environment:

1. *Light* affects the perception of visual information. Dim light makes content hard to see, while light that is too bright can cause reflection on the screen, commonly known as discomfort glare (Choe and Lee, 2015); see Figure 2e. Discomfort glare can be corrected by adjusting device orientation and/or position. Interested in this phenomenon, Kelley et al. (2006) proposed a procedure to characterize the dynamic range, contrast, and readability of a display under daylight conditions and Rodriguez et al. (2016) examined the effect of sunlight glare on cognitive performance. Light can cause even more discomfort when eye disorders are already present, such as photophobia.

2. *Environment phenomena*. Natural phenomena occurring in the physical environment, *e.g.*, rain, strong wind, or dust, can temporarily affect perception of visual content and the interaction because corrective measures need to be applied, such as adjusting position and orientation or covering the screen for protection using the other hand.

3. *Context of use*. Some physical environments, such as underwater for example (Koike et al., 2013; Pier and Goldberg, 2005), make perception of visual information more difficult. Dangerous working conditions may require equipment for protection, such as special glasses. Generally, protection equipment (gloves, special clothes, head protection gear) make interaction with small mobile devices more difficult by reducing users' comfort and capacity to control the device (*e.g.*, gloves) or to perceive visual content effectively (safety glasses).

3.4 The social environment

Social norms, formal requirements governing behavior in polite society, and regulations impact *when* and *how* mobile devices should be used. For instance, when engaged in a social activity, such as a meeting, having phone call interruptions may be negatively perceived by others. Anderson et al. (2015) devised alternative approaches to operate mobile devices in subtle ways. Rico and Brewster (2009, 2010) investigated the social acceptability of motion gestures performed with mobile devices and found that *location* and *audience* have a significant impact on a user's willingness to perform motion gestures in public. Such aspects add on top of the challenges created by pathological visual impairment. For instance, Jackson and Gleeson (2013) observed a perceived or actual negative social bias that determine problems in self-image and interpersonal relationships affecting people with strabismus. Shinohara and Tenenberg (2007) presented the case study of a blind person's interactions with technology and pointed to the importance of having assistive technology that does not "mark" the user as blind. Furthermore, regulations prevent mobile phone usage in some contexts, such as while driving. Abdolrahmani et al. (2016) examined situationally-induced impairments on mobile devices for people who are blind and reported on the challenges of using screen readers during meetings. Workaround solutions adopted by people who are blind were to wear earphones, minimize the audio volume, or to attenuate the audio output by placing their fingers on the phone's speaker; see (Abdolrahmani et al., 2016) for more discussion. These examples show how the social environment represents an important dimension to consider for assistive interface design for mobile devices.

4. DESIGN GUIDELINES FOR TOUCH AND GESTURE INPUT ON MOBILE DEVICES

In this section, we summarize previous design guidelines from the accessibility literature to improve the accessibility of mobile devices for people with visual impairments. We group previous recommendations in 15 discussion points, ranging from general accessibility and usability aspects of mobile devices up to specific challenges for touch and gesture input:

1. **Design new form factors for accessible mobile devices.** Blind people do not need the (usually large) visual display present on today's smartphones and, therefore, the display size and the form factor of the device can be reduced to a minimum size allowed by manufacturing processes and usability criteria (Ye et al., 2014). Because mobile devices, such as tablets and smartphones, need to be carried around, reached for before use, and then stored away when not in use, wearable devices that are always attached to fixed locations on the body, such as the wrist or the ear, could represent a suitable alternative to smartphones for people with visual impairments; see next.

2. **Design for commercially-available wearable devices.** Recent advances in miniaturization and mobile computing spurred a wide range of wearable devices that are commercially available today, such as wristbands meters, smartwatches, augmented reality glasses, GPS trackers, and so on. Previous work has found that wearable devices were positively received by people with visual impairments (Ye et al., 2014). Because these devices are worn at fixed locations on the body (*e.g.*, the wrist), they are easy to access due to proprioception mechanisms and, thus, cannot

be misplaced; also, they do not need to be stored when not in used, making access to them more efficient. Wearable devices come with on-board sensors and electronics that enable many opportunities for non-visual input and output. For instance, vibrotactile feedback can be delivered at various locations on the hand, *e.g.*, on the wrist (Schönauer et al., 2015; Ye et al., 2014) or a on the arms and the body (Lindeman et al., 2004; Meier et al., 2015). Audio feedback can be personalized to one's ears only with smart earbuds, some with touch sensing embedded, such as The Dash (Bragi, 2016). Visual feedback head-mounted displays and augmented reality glasses can enhance the perception of the visual reality for many applications and for a wide range of visual abilities; see Hwang and Peli (2014); Tanuwidjaja et al. (2014); Zhao et al. (2015, 2016) for a few examples of such systems.

3. **Design interactions for multiple mobile devices.** People with visual impairments make use of complementary devices when interacting with their smartphones, such as keyboards or refreshable Braille displays (Ye et al., 2014). Recently, cross-device interaction techniques have emerged, which enable designing interactions for multiple smart mobile devices (Chi and Li, 2015; Chi et al., 2016; Rädle et al., 2015; Vatavu et al., 2016), but more explorations and studies are needed to understand user performance in such multi-device interactive contexts.

4. **Design mobile device interactions to reduce encumbrance when using other accessibility devices.** People with visual impairments carry and use accessibility devices, such as canes, magnifiers, Braille compasses, wired headphones, refreshable Braille displays, etc. (Kane et al., 2009; Ye et al., 2014) or may have their hands busy holding, for example, the leash for service dogs. Consequently, hands may already be occupied, making only one hand available for

interacting with the mobile device (Abdolrahmani et al., 2016). Such constraints that combine pathological and situational factors of visual impairment demand efficient single-hand input techniques to be designed for effective mobile device use.

5. **Allow configurable visual settings.** Although settings on most smart devices are configurable (*e.g.*, text can be made larger, and the palette of colors is customizable), devices should also allow arbitrary settings, instead of preselected configurations. Previous studies showed that people with visual impairments are willing to spend time configuring a device before using it, if those adjustments will help later (Kane et al., 2009). Schuchhardt et al. (2015) observed that current adaptive display brightness schemes are not well-tuned to users' preferences.

6. **Detect and use context.** In some contexts, using a mobile device may prove difficult or actually unsafe. Sensing the context (*e.g.*, information about the user, location, activity, etc.) with available on-board sensors (*e.g.*, accelerometers, gyroscopes, light sensors, microphones, etc.) should be explored more in order to adapt the interface to users and their activities (Abdolrahmani et al., 2016; Kane et al., 2009; Mariakakis et al., 2015).

7. **Design discrete interactions.** There are social scenarios where people need to interact with their devices without drawing attention, *e.g.*, reading an important text message that has just arrived, when in a meeting. Such "discrete" interactions are more challenging for people with visual impairments, and the literature has highlighted the need for assistive technology to implement such interactions, without drawing attention to themselves (Abdolrahmani et al., 2016; Kane et al., 2009; Shinohara and Tenenberg, 2007). New sensing technology for non-

touch gestures (Chen et al., 2014; Hinckley et al., 2016; Song et al., 2014) or technology that would not require actually reaching for the device (Dezfuli et al., 2012; Gustafson et al., 2011) might prove useful in this direction, as well as adoption and adaptation of subtle interaction techniques (Anderson et al., 2015) for people with visual impairments.

8. **Detect and deal appropriately with unintended touch.** Unintended touches can cause accidental activation of device features, changing contexts, or launching other applications (McGookin et al., 2008). Previous studies showed that people with visual impairments are concerned about such usability aspects of touchscreens (Kane et al., 2008a), because it is difficult for them to know how far above the screen their fingers are (McGookin et al., 2008). Other causes for unintended touch are resting the palm on some region of the device, fingers touching the screen because of the grasp, trailing fingers on the touch surface, hand shaking or fingers slipping (El-Glaly et al., 2012). Rejecting unintended touch is also problem for users with full sight; see Annett et al. (2014). There are several ways to prevent unintended touch implementable at the level of gesture set design or at the level of sensing touches and finger movements. For example, the applicability of simple taps and short gestures can be restricted in some contexts (McGookin et al., 2008). Consistent movement (*e.g.*, left to right for a text to speech app) could be tracked by keeping a record of previous touches and use it to detect those touches far-away from the trend (El-Glaly et al., 2012), or using filtering criteria that reject up to 80% of the unintended touches (Matero and Colley, 2012). Recent pre-touch sensing techniques (Hinckley et al., 2016) could detect in advance when the fingers or the palm approach the surface and, therefore, inform appropriate actions. Also, sensing the grasping style of the user (Goel et

al., 2012b; Wolf and Henze, 2014; Yoon et al., 2015) could also help applications to ignore unintended touches occurring at the edges of the touchscreen, for instance.

9. **Design usable touch gestures for people with visual impairments.** Gestures performed by people who are blind on touchscreens differ from those articulated by sighted people and, therefore, generic guidelines from the gesture design literature (Wobbrock et al., 2009; Rekik et al., 2013, 2014; Morris et al., 2010; Nacenta et al., 2013) do not equally apply for people who are blind. Instead, touch gestures for people with visual impairments should make use of mode changers, favor edges, corners, and other physical landmarks on the device (Kane et al., 2011b), favor short and single-stroke gestures (Buzzi et al., 2016), avoid gesture shapes with right or steep angle, and use directional strokes (Buzzi et al., 2016). Also, some gesture shapes should be avoided, such as letters, numbers, and other symbols, as people who are blind may not know to perform them or may not have sufficient practice performing them accurately (Kane et al., 2011a; Buzzi et al., 2016). Gestures that require users to start interacting on specific locations on the screen should also be avoided (McGookin et al., 2008) unless common layouts, such as QWERTY for instance, can be leveraged (Kane et al., 2011b). Some studies also observed that people who are blind perform gestures that sometimes continue outside the boundaries of the display (Buzzi et al., 2015), in which case the application would incorrectly infer that the gesture has ended. These observations suggest the need for better design of gesture sets for people with visual impairments, but also point to new design opportunities, such as extending touch gestures above and beyond the display. Multi-touch gesture design approaches could be adapted to propose usable gestures for people with visual impairments for specific applications (Park and Han, 2014). In-air gesture and non-touch gesture sensing (Chen et al., 2014; Song et al., 2014;

Arefin Shimon et al., 2016) may prove useful to deal with such situations and also to extend the gesture design space.

10. **Develop new recognition techniques or adapt current gesture recognizers to gestures articulated by people with visual impairments.** The only available data on recognition performance of gestures produced by people who are blind comes from Kane et al. (2011b), who employed the \$N recognizer of Anthony and Wobbrock (2010) and reported recognition rates between 44.9% and 78.7% depending on the training condition. This limited information shows critical need for more evaluations of gesture recognition performance for people with visual impairments, as well as more efforts to develop gesture recognizers that can appropriately handle articulation variations produced by people with visual impairments. Kane et al. (2011b) observed that people with visual impairments use multiple fingers and create more strokes per gesture than people without impairments, which suggests the need for gesture recognizers that are invariant to such articulation details. The \$P point-cloud gesture recognizer (Vatavu et al., 2012) represents such an approach that was shown to deliver high accuracy on a wide range of gesture types, but unfortunately it was not evaluated on gestures produced by people with visual impairments. Also, people who are blind produce more variations in the gestures they articulate than sighted people (Kane et al., 2011b; Buzzi et al., 2016),, which recommends the use of gesture recognizers that are more tolerant to geometric and kinematic variations. Especially variations in production time and speed (*e.g.*, people who are blind perform gestures at a different pace than sighted people; see (Kane et al., 2011b)) suggest that gesture recognizers should not rely their decisions on kinematic features (Blagojevic et al., 2010; Rubine, 1991). The effect of gesture implementer also needs to be considered. Previous findings (for participants with full sight)

found that differences exist between gestures produced with the finger and the stylus (Tu et al., 2015, 2014) and, consequently, researchers and practitioners should also consider how such aspects scale to people with visual impairments.

11. **Deliver appropriate feedback for all visual abilities.** It is important to provide feedback for all actions on touchscreens, and feedback type should be adapted to a wide range of visual abilities. This work has surveyed a lot of techniques to render visual content in non-visual ways. However, feedback modalities should also take account of context. For instance, audio feedback may be challenging to process outdoor, where people with visual impairments need to focus on ambient sounds, such as noise traffic for orientation and navigation (Abdolrahmani et al., 2016; Kane et al., 2009). McGookin et al. (2008) found that participants with visual impairments generally prefer audio feedback, but people with low vision prefer to rely on their visual abilities instead of receiving aural feedback (Szpiro et al., 2016a). Feedback should also be delivered as early as possible to the user (Abdolrahmani et al., 2016).

12. **Deliver appropriate feedback during and after gesture articulation.** It is important to provide feedback *during* and *after* gesture articulation to inform users about correct gesture articulation and also about correct interpretation by the system, because finger slips or temporarily not sensing touch may determine that gestures are not registered as intended (Buzzi et al., 2015). Gesture sonification techniques (Oh et al., 2015) and vibrotactile output at arm level (Sch¨onauer et al., 2015) can help delivering such feedback, while more work is needed to adapt techniques implementing gesture feedforward (Bau and Mackay, 2008; Delamare et al., 2016) for people with visual impairments.

13. **Design appropriate techniques for learning gestures.** More techniques are needed to help people who are blind learn gesture sets, because the current approaches from the literature (Bau and Mackay, 2008; Delamare et al., 2016; Kurtenbach et al., 1994) rely exclusively on visual stimuli to help memory recall. Audio-based feedback techniques (Oh et al., 2015), eyes-free techniques that rely on proprioception (Dezfuli et al., 2012; Gustafson et al., 2011), or recent approaches for haptic learning (Gupta et al., 2016) are likely to be useful for this purpose, yet they still need to be adapted and evaluated for people with visual impairments.

14. **Design new assistive features for screen readers.** Many advances in screen reader technology have been introduced in the recent years to overcome various accessibility problems, with VoiceOver and Google TalkBack being largely used by people with visual impairments (Apple, 2016; Google, 2016b). However, studies examining accessibility and usability aspects of screen readers, such as VoiceOver, outlined frequently-reported problems, such as interactive elements not being always clearly described and pointed to aspects regarding the logical navigation order of elements in a list (Leporini et al., 2012; Tomlinson et al., 2016). A few recent efforts are notable however, such as captioning photos and videos (Larson, 2016a,b) and automating alternative text for images with object recognition (Garcia et al., 2016). Nevertheless, other challenges exist, such as screen readers not handling appropriately various touch input behavior (Goh and Kim, 2014) and not scaling well to large touchscreen surfaces (Kane et al., 2011a). Also, previous work indicated that gesture commands for screen readers could benefit of further simplification to allow single-handed use of the device or safe use during walking (Abdolrahmani et al., 2016; Kuber et al., 2012).

15. **Evaluate assistive technology in real-world scenarios**. It is important to evaluate assistive technology in the actual context where it will be used. For instance, audio feedback has been frequently proposed to substitute visual perception of on-screen elements. However, audio is perceived differently in conditions of traffic noise outdoor than in the lab (Abdolrahmani et al., 2016), which may impact its efficiency for some scenarios. Most gesture recognition algorithms have been evaluated with gestures collected in controlled conditions, with participants seated or detached from distracting stimuli (Anthony and Wobbrock, 2010; Vatavu et al., 2012; Wobbrock et al., 2007) and, therefore, more evaluations of gesture recognition performance are needed for visual impairing interaction contexts.

5. CONCLUSION

This work presented the first survey of touchscreen interaction and visual impairments and introduced the first catalogue of factors responsible for visual impairment in the context of mobile touch input. As is, the catalogue already contains a variety of factors that affect interaction effectiveness on mobile devices and that need to be considered for the design of assistive techniques. Future work and practice of designing mobile touchscreen user interfaces for people with visual impairments and for situationally-induced visual impairments will likely improve the catalogue by identifying new causes and connections to existing factors. The goal of this work was to help systematize research on visual impairments and mobile touchscreen interaction by providing an overview of the main causes of visual impairments affecting touchscreen interaction effectiveness and efficiency on smart mobile devices. We hope that the survey and catalogue will benefit the community and inspire new work to better understand causes of visual impairment for mobile touchscreen interaction and to design and develop better assistive technology for a wide range of visual abilities.

ACKNOWLEDGMENTS

This work was supported from the project *"Gesture interfaces for visually-impairing interaction contexts"*, project no. PN-II-RU-TE-2014-4-1187, financed by UEFISCDI, Romania. The work was carried out in the Machine Intelligence and Information Visualization Lab (MintViz) of the MANSiD Research Center. The infrastructure was provided by the University of Suceava and was partially supported from the project *"Integrated center for research, development and innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for fabrication and control"*, No. 671/09.04.2015, Sectoral Operational Program for Increase of the Economic Competitiveness, co-funded from the European Regional Development Fund. The author would like to thank the anonymous reviewers for thoughtful comments and suggestions, Sam Waller for granting permission to include pictures processed with the Vision and Hearing Impairment Simulator (Figures 1 and 5), and Gabriel Cramariuc for photo credit for Figure 7.

References

Abdolrahmani, A., Kuber, R., and Hurst, A. (2016). An empirical investigation of the situationally-induced impairments experienced by blind mobile device users. In *Proceedings of the 13th Web for All Conference*, W4A '16, pages 21:1–21:8, New York, NY, USA. ACM.

Anderson, F., Grossman, T., Wigdor, D., and Fitzmaurice, G. (2015). Supporting subtlety with deceptive devices and illusory interactions. In *Proceedings of the 33rd Annual ACM*

Conference on Human Factors in Computing Systems, CHI ’15, pages 1489–1498, New York, NY, USA. ACM.

Annett, M., Gupta, A., and Bischof, W. F. (2014). Exploring and understanding unintended touch during direct pen interaction. *ACM Trans. Comput.-Hum. Interact.*, 21(5):28:1–28:39.

Anthony, L., Vatavu, R.-D., and Wobbrock, J. O. (2013). Understanding the consistency of users’ pen and finger stroke gesture articulation. In *Proceedings of Graphics Interface 2013*, GI ’13, pages 87–94, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

Anthony, L. and Wobbrock, J. O. (2010). A lightweight multistroke recognizer for user interface prototypes. In *Proceedings of Graphics Interface 2010*, GI ’10, pages 245–252, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

AppdLab (2016). Magnify. https://goo.gl/SEMhlH.

Appert, C., Chapuis, O., and Pietriga, E. (2010). High-precision magnification lenses. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’10, pages 273–282, New York, NY, USA. ACM.

Apple (2016). Voiceover for iOS. Let our voice be your guide. http://www.apple.com/accessibility/ios/voiceover/.

Appollonio, I., Carabellese, C., Frattola, L., and Trabucchi, M. (1996). Effects of sensory aids on the quality of life and mortality of elderly people: a multivariate analysis. *Age Ageing*, 25(2):89–96.

Arefin Shimon, S. S., Lutton, C., Xu, Z., Morrison-Smith, S., Boucher, C., and Ruiz, J. (2016). Exploring non-touchscreen gestures for smartwatches. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 3822–3833, New York, NY, USA. ACM.

Ash, D., Keegan, D., and Greenough, T. (1978). Factors in adjustment to blindness. *Canadian Journal of Ophthalmology*, 13(1):15–21.

Azenkot, S., Bennett, C. L., and Ladner, R. E. (2013). Digitaps: Eyes-free number entry on touchscreens with minimal audio feedback. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*, UIST '13, pages 85–90, New York, NY, USA. ACM.

Azenkot, S., Prasain, S., Borning, A., Fortuna, E., Ladner, R. E., and Wobbrock, J. O. (2011). Enhancing independence and safety for blind and deaf-blind public transit riders. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 3247–3256, New York, NY, USA. ACM.

Azenkot, S., Rector, K., Ladner, R., and Wobbrock, J. (2012a). Passchords: Secure multi-touch authentication for blind people. In *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '12, pages 159–166, New York, NY, USA. ACM.

Azenkot, S., Wobbrock, J. O., Prasain, S., and Ladner, R. E. (2012b). Input finger detection for nonvisual touch screen text entry in perkinput. In *Proceedings of Graphics Interface 2012*, GI '12, pages 121–129, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

Azenkot, S. and Zhai, S. (2012). Touch behavior with different postures on soft smartphone keyboards. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services*, MobileHCI '12, pages 251–260, New York, NY, USA. ACM.

Azrak, C., Palazón-Bru, A., Baeza-Díaz, M., la Rosa, D. F.-D., Hernández-Martínez, C., Martínez-Toldos, J., and Gil-Guillén, V. (2015). A predictive screening tool to detect diabetic retinopathy or macular edema in primary health care: construction, validation and implementation on a mobile application. *PeerJ*, 3:e1404:1–10.

Bacim, F., Sinclair, M., and Benko, H. (2013). Understanding touch selection accuracy on flat and hemispherical deformable surfaces. In *Proceedings of Graphics Interface 2013*, GI '13, pages 197–204, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

Barnard, L., Yi, J. S., Jacko, J. A., and Sears, A. (2007). Capturing the effects of context on human performance in mobile computing systems. *Personal Ubiquitous Comput.*, 11(2):81–96.

Bau, O. and Mackay, W. E. (2008). Octopocus: A dynamic guide for learning gesture-based command sets. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*, UIST '08, pages 37–46, New York, NY, USA. ACM.

Bigham, J., Jayant, C., Miller, A., White, B., and Yeh, T. (2010). VizWiz::LocateIt enabling blind people to locate objects in their environment. In *Proceedings of the CVPR Workshop: Computer Vision Applications for the Visually Impaired*.

Bischof, W., Krajnc, E., Dornhofer, M., and Ulm, M. (2012). Navcom-wlan communication between public transport vehicles and smart phones to support visually impaired and blind people. In *Proceedings of the 13th International Conference on Computers Helping People with Special Needs*, ICCHP '12, pages 91–98. Springer-Verlag.

Blagojevic, R., Chang, S. H.-H., and Plimmer, B. (2010). The power of automatic feature selection: Rubine on steroids. In *Proceedings of the Seventh Sketch-Based Interfaces and Modeling Symposium*, SBIM '10, pages 79–86, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.

Brady, E., Morris, M. R., Zhong, Y., White, S., and Bigham, J. P. (2013). Visual challenges in the everyday lives of blind people. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 2117–2126, New York, NY, USA. ACM.

Bragi (2016). Bragi - The Dash. http://www.bragi.com/thedash/.

Burch, D. S. and Pawluk, D. T. (2009). A cheap, portable haptic device for a method to relay 2-d texture-enriched graphical information to individuals who are visually impaired. In *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '09, pages 215–216, New York, NY, USA. ACM.

Buzzi, M., Buzzi, M., Leporini, B., and Martusciello, L. (2011). Making visual maps accessible to the blind. In *Proceedings of the 6th International Conference on Universal Access in Human-Computer Interaction: Users Diversity*, UAHCI'11, pages 271–280, Berlin, Heidelberg. Springer-Verlag.

Buzzi, M. C., Buzzi, M., Leporini, B., and Trujillo, A. (2015). Exploring visually impaired people's gesture preferences for smartphones. In *Proceedings of the 11th Biannual Conference on Italian SIGCHI Chapter*, CHItaly 2015, pages 94–101, New York, NY, USA. ACM.

Buzzi, M. C., Buzzi, M., Leporini, B., and Trujillo, A. (2016). Analyzing visually impaired people's touch gestures on smartphones. *Multimeda Tools and Applications*, pages 1–29.

Chang, Y., L'Yi, S., Koh, K., and Seo, J. (2015). Understanding users' touch behavior on large mobile touch-screens and assisted targeting by tilting gesture. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 1499–1508, New York, NY, USA. ACM.

Chen, D., Feng, W., Zhao, Q., Hu, M., and Wang, T. (2012). An infrastructure-free indoor navigation system for blind people. In *Proceedings of the 5th International Conference on Intelligent Robotics and Applications*, ICIRA '12, pages 552–561, Berlin, Heidelberg. Springer-Verlag.

Chen, X. A., Schwarz, J., Harrison, C., Mankoff, J., and Hudson, S. E. (2014). Air+touch: Interweaving touch & in-air gestures. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST '14, pages 519–525, New York, NY, USA. ACM.

Chhetri, A. P., Wen, F., Wang, Y., and Zhang, K. (2010). Shape discrimination test on handheld devices for patient self-test. In *Proceedings of the 1st ACM International Health Informatics Symposium*, IHI '10, pages 502–506, New York, NY, USA. ACM.

Chi, P.-Y. P. and Li, Y. (2015). Weave: Scripting cross-device wearable interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 3923–3932, New York, NY, USA. ACM.

Chi, P.-Y. P., Li, Y., and Hartmann, B. (2016). Enhancing cross-device interaction scripting with interactive illustrations. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 5482–5493, New York, NY, USA. ACM.

Choe, W. and Lee, M. W. (2015). Discomfort glare model for mobile display. In *Proceedings of the IEEE 5th International Conference on Consumer Electronics*, pages 471–473.

Csapó, A., Wersényi, G., Nagy, H., and Stockman, T. (2015). A survey of assistive technologies and applications for blind users on mobile platforms: a review and foundation for research. *Journal on Multimodal User Interfaces*, 9(4):275–286.

Delamare, W., Janssoone, T., Coutrix, C., and Nigay, L. (2016). Designing 3d gesture guidance: Visual feedback and feedforward design options. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, AVI '16, pages 152–159, New York, NY, USA. ACM.

Dezfuli, N., Khalilbeigi, M., Huber, J., Müller, F., and Mühlhäuser, M. (2012). PalmRC: Imaginary palm-based remote control for eyes-free television interaction. In *Proceedings of the 10th European Conference on Interactive Tv and Video*, EuroiTV '12, pages 27–34, New York, NY, USA. ACM.

El-Glaly, Y., Quek, F., Smith-Jackson, T., and Dhillon, G. (2012). Audible rendering of text documents controlled by multi-touch interaction. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction*, ICMI '12, pages 401–408, New York, NY, USA. ACM.

Elton, E. and Nicolle, C. (2010). The importance of context in inclusive design. *Contemporary Ergonomics*, pages 1–16.

Encelle, B., Ollagnier-Beldame, M., Pouchot, S., and Prié, Y. (2011). Annotation-based video enrichment for blind people: A pilot study on the use of earcons and speech synthesis. In *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '11, pages 123–130, New York, NY, USA. ACM.

Eriksen, C. W. and Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics*, 12(2):201–204.

Eriksen, C. W. and James, J. D. S. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, 40(4):225–240.

Exler, A., Braith, M., Schankin, A., and Beigl, M. (2016). Preliminary investigations about interruptibility of smartphone users at specific place types. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, UbiComp '16, pages 1590–1595, New York, NY, USA. ACM.

Frey, B., Southern, C., and Romero, M. (2011). Brailletouch: Mobile texting for the visually impaired. In *Proceedings of the 6th International Conference on Universal Access in Human-computer Interaction: Context Diversity - Volume Part III*, UAHCI'11, pages 19–25, Berlin, Heidelberg. Springer-Verlag.

Gajos, K. and Weld, D. S. (2004). Supple: Automatically generating user interfaces. In *Proceedings of the 9th International Conference on Intelligent User Interfaces*, IUI '04, pages 93–100, New York, NY, USA. ACM.

Gajos, K. Z., Weld, D. S., and Wobbrock, J. O. (2010). Automatically generating personalized user interfaces with supple. *Artif. Intell.*, 174(12-13):910–950.

Gajos, K. Z., Wobbrock, J. O., and Weld, D. S. (2007). Automatically generating user interfaces adapted to users' motor and vision capabilities. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology*, UIST '07, pages 231–240, New York, NY, USA. ACM.

Garcia, D. G., Paluri, M., and Wu, S. (2016). Under the hood: Building accessibility tools for the visually impaired on facebook.

GeorgiePhone (2016). Smart android apps for blind people. http://www.georgiephone.com/.

Giachritsis, C., Randall, G., and Roselier, S. (2012). Development of intuitive tactile navigational patterns. In *Proceedings of the 2012 International Conference on Haptics: Perception, Devices, Mobility, and Communication - Volume Part I*, EuroHaptics'12, pages 136–147, Berlin, Heidelberg. Springer-Verlag.

Goel, M., Findlater, L., and Wobbrock, J. (2012a). Walktype: Using accelerometer data to accomodate situational impairments in mobile touch screen text entry. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, pages 2687–2696, New York, NY, USA. ACM.

Goel, M., Jansen, A., Mandel, T., Patel, S. N., and Wobbrock, J. O. (2013). Contexttype: Using hand posture information to improve mobile touch screen text entry. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 2795–2798, New York, NY, USA. ACM.

Goel, M., Wobbrock, J., and Patel, S. (2012b). Gripsense: Using built-in sensors to detect hand posture and pressure on commodity mobile phones. In *Proceedings of the 25th Annual ACM*

Symposium on User Interface Software and Technology, UIST '12, pages 545–554, New York, NY, USA. ACM.

Goh, T. and Kim, S. W. (2014). Eyes-free text entry interface based on contact area for people with visual impairment. In *Proceedings of the Adjunct Publication of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST'14 Adjunct, pages 69–70, New York, NY, USA. ACM.

Gollner, U., Bieling, T., and Joost, G. (2012). Mobile lorm glove: Introducing a communication device for deaf-blind people. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, TEI '12, pages 127–130, New York, NY, USA. ACM.

Google (2016a). Accessibility | android developers. https://developer.android.com/design/patterns/accessibility.html.

Google (2016b). Google TalkBack. https://goo.gl/t43nNu.

Grossman, T. and Balakrishnan, R. (2005). The bubble cursor: Enhancing target acquisition by dynamic resizing of the cursor's activation area. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, pages 281–290, New York, NY, USA. ACM.

Guerreiro, T., Lagoá, P., Nicolau, H., Gonçalves, D., and Jorge, J. A. (2008). From tapping to touching: Making touch screens accessible to blind users. *IEEE MultiMedia*, 15(4):48–50.

Guerreiro, T., Oliveira, J., Benedito, J., Nicolau, H., Jorge, J., and GonÃ§alves, D. (2011). Blind people and mobile keypads: accounting for individual differences. In *Proceedings of the 13th IFIP TC 13 International Conference on Human-Computer Interaction*, INTERACT'11, pages 65–82. Springer-Verlag.

Gupta, A., Irudayaraj, A., Chandran, V., Palaniappan, G., Truong, K. N., and Balakrishnan, R. (2016). Haptic learning of semaphoric finger gestures. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16, pages 219–226, New York, NY, USA. ACM.

Gustafson, S., Holz, C., and Baudisch, P. (2011). Imaginary phone: Learning imaginary interfaces by transferring spatial memory from a familiar device. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, pages 283–292, New York, NY, USA. ACM.

Hakobyan, L., Lumsden, J., and O'Sullivan, D. (2014). Participatory research with older adults with amd: Co-designing a smart diet diary app. In *Proceedings of the 28th International BCS Human Computer Interaction Conference on HCI 2014 - Sand, Sea and Sky - Holiday HCI*, BCS-HCI '14, pages 32–41, UK. BCS.

Hakobyan, L., Lumsden, J., O'Sullivan, D., and Bartlett, H. (2013). Designing a mobile diet diary application with and for older adults with amd: A case study. In *Proceedings of the 27th International BCS Human Computer Interaction Conference*, BCS-HCI '13, pages 17:1–17:10, Swinton, UK, UK. British Computer Society.

HaptiMap. Haptimap, haptic, audio and visual interfaces for maps and location based services. http://www.haptimap.org/.

Hersh, M. and Johnson, M. A., editors (2008). *Assistive Technology for Visually Impaired and Blind People*. Springer.

Hinckley, K., Heo, S., Pahud, M., Holz, C., Benko, H., Sellen, A., Banks, R., O'Hara, K., Smyth, G., and Buxton, W. (2016). Pre-touch sensing for mobile interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 2869–2881, New York, NY, USA. ACM.

Holz, C. and Baudisch, P. (2011). Understanding touch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 2501–2510, New York, NY, USA. ACM.

Hwang, A. and Peli, E. (2014). An augmented-reality edge enhancement application for google glass. *Optometry & Vision Science*, 91(8):1021–1030.

Jacko, J. A. and Sears, A. (1998). Designing interfaces for an overlooked user group: Considering the visual profiles of partially sighted users. In *Proceedings of the Third International ACM Conference on Assistive Technologies*, Assets '98, pages 75–77, New York, NY, USA. ACM.

Jackson, S. and Gleeson, K. (2013). Living and coping with strabismus as an adult. *European Medical Journal Ophthalmology*, pages 15–22.

Jafri, R., Ali, S. A., Arabnia, H. R., and Fatima, S. (2014). Computer vision-based object recognition for the visually impaired in an indoors environment: A survey. *Vis. Comput.*, 30(11):1197–1222.

Kane, S. K., Bigham, J. P., and Wobbrock, J. O. (2008a). Slide rule: Making mobile touch screens accessible to blind people using multi-touch interaction techniques. In *Proceedings of* *the 10th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '08, pages 73–80, New York, NY, USA. ACM.

Kane, S. K., Frey, B., and Wobbrock, J. O. (2013a). Access lens: A gesture-based screen reader for real-world documents. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 347–350, New York, NY, USA. ACM.

Kane, S. K., Jayant, C., Wobbrock, J. O., and Ladner, R. E. (2009). Freedom to roam: A study of mobile device adoption and accessibility for people with visual and motor disabilities. In *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '09, pages 115–122, New York, NY, USA. ACM.

Kane, S. K., Morris, M. R., Perkins, A. Z., Wigdor, D., Ladner, R. E., and Wobbrock, J. O. (2011a). Access overlays: Improving non-visual access to large touch screens for blind users. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, pages 273–282, New York, NY, USA. ACM.

Kane, S. K., Morris, M. R., and Wobbrock, J. O. (2013b). Touchplates: Low-cost tactile overlays for visually impaired touch screen users. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '13, pages 22:1–22:8, New York, NY, USA. ACM.

Kane, S. K., Wobbrock, J. O., and Ladner, R. E. (2011b). Usable gestures for blind people: Understanding preference and performance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 413–422, New York, NY, USA. ACM.

Kane, S. K., Wobbrock, J. O., and Smith, I. E. (2008b). Getting off the treadmill: Evaluating walking user interfaces for mobile devices in public spaces. In *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services*, MobileHCI '08, pages 109–118, New York, NY, USA. ACM.

Karikoski, J. and Soikkeli, T. (2013). Contextual usage patterns in smartphone communication services. *Personal Ubiquitous Comput.*, 17(3):491–502.

Karim, S., Andjomshoaa, A., and Tjoa, A. M. (2006). Exploiting sensecam for helping the blind in business negotiations. In *Proceedings of the 10th International Conference on Computers Helping People with Special Needs*, ICCHP '06, pages 1147–1154, Berlin, Heidelberg. Springer-Verlag.

Kelley, E. F., Lindfors, M., and Penczek, J. (2006). Display daylight ambient contrast measurement methods and daylight readability. *Journal of the Society for Information Display*, 14:1019â€"–1030.

Kempen, G. I. and Zijlstra, G. R. (2014). Clinically relevant symptoms of anxiety and depression in low-vision community-living older adults. *The American Journal of Geriatric Psychiatry*, 22(3):309â€"–313.

Khademi, M., Mousavi Hondori, H., and Videira Lopes, C. (2012). Optical illusion in augmented reality. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology*, VRST '12, pages 195–196, New York, NY, USA. ACM.

Kim, D.-j. and Lim, Y.-k. (2011). Handscope: Enabling blind people to experience statistical graphics on websites through haptics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 2039–2042, New York, NY, USA. ACM.

Kim, H. N., Smith-Jackson, T. L., and Nam, C. S. (2013). Elicitation of haptic user interface needs of people with low vision. *International Journal of Humanâ€“Computer Interaction*, 29(7):488–500.

Koike, H., Matoba, Y., and Takahashi, Y. (2013). Aquatop display: Interactive water surface for viewing and manipulating information in a bathroom. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces*, ITS '13, pages 155–164, New York, NY, USA. ACM.

Krajnc, E., Feiner, J., and Schmidt, S. (2010). User centered interaction design for mobile applications focused on visually impaired and blind people. In *Proceedings of the 6th international conference on HCI in work and learning, life and leisure: workgroup human-computer interaction and usability engineering*, USAB '10, pages 195–202. Springer-Verlag.

Kuber, R., Hastings, A., Tretter, M., and Fitzpatrick, D. (2012). Determining the accessibility of mobile screen readers for blind users. In *Proceedings of the IASTED Conference on Human-Computer Interaction*, pages 182–189.

Kurtenbach, G. and Buxton, W. (1994). User learning and performance with marking menus. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '94, pages 258–264, New York, NY, USA. ACM.

Kurtenbach, G., Moran, T., and Buxton, W. (1994). Contextual animation of gestural commands. *Computer Graphics Forum*, 13(5):305–314.

Landau, S. and Wells, L. (2003). Merging tactile sensory input and audio data by means of the talking tactile tablet. In *Proceedings of EuroHaptics '03*, pages 414–418. IEEE Computer Society.

Larson, S. (2016a). How tech companies are making their apps more accessible to the disabled. http://theweek.com/articles/628552/how-tech-companies-are-making-apps-more-accessible-disabled.

Larson, S. (2016b). Twitter finally adds photo captioning for the visually impaired. http://www.dailydot.com/debug/twitter-alt-text-captioning/.

Lee, S. and Zhai, S. (2009). The performance of touch screen soft buttons. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 309–318, New York, NY, USA. ACM.

Leonard, V. K., Jacko, J. A., and Pizzimenti, J. J. (2005). An exploratory investigation of handheld computer interaction for older adults with visual impairments. In *Proceedings of the 7th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '05, pages 12–19, New York, NY, USA. ACM.

Leporini, B., Buzzi, M. C., and Buzzi, M. (2012). Interacting with mobile devices via voiceover: Usability and accessibility issues. In *Proceedings of the 24th Australian Computer-Human Interaction Conference*, OzCHI '12, pages 339–348, New York, NY, USA. ACM.

Lévesque, V., Pasquero, J., Hayward, V., and Legault, M. (2005). Display of virtual braille dots by lateral skin deformation: Feasibility study. *ACM Trans. Appl. Percept.*, 2(2):132–149.

Li, F. C. Y., Dearman, D., and Truong, K. N. (2010). Leveraging proprioception to make mobile phones more accessible to users with visual impairments. In *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '10, pages 187–194, New York, NY, USA. ACM.

Lindeman, R. W., Page, R., Yanagida, Y., and Sibert, J. L. (2004). Towards full-body haptic feedback: The design and deployment of a spatialized vibrotactile feedback system. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '04, pages 146–149, New York, NY, USA. ACM.

Mack, A., Pappas, Z., Silverman, M., and Gay, R. (2002). What we see: Inattention and the capture of attention by meaning. *Consciousness and Cognition*, 11(4):488â€“–506.

Mack, A. and Rock, I. (1998). *Inattentional Blindness*. MIT Press.

Manduchi, R. and Coughlan, J. (2012). (Computer) vision without sight. *Commun. ACM*, 55(1):96–104.

Manohar, P. and Parthasarathy, A. (2009). An innovative braille system keyboard for the visually impaired. In *Proceedings of the 11th International Conference on Computer Modelling and Simulation*, UKSIM '09, pages 559–562.

Mariakakis, A., Goel, M., Aumi, M. T. I., Patel, S. N., and Wobbrock, J. O. (2015). Switchback: Using focus and saccade tracking to guide users' attention for mobile task resumption. In

Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, CHI ’15, pages 2953–2962, New York, NY, USA. ACM.

Matero, J. and Colley, A. (2012). Identifying unintentional touches on handheld touch screen devices. In *Proceedings of the Designing Interactive Systems Conference*, DIS ’12, pages 506–509, New York, NY, USA. ACM.

McGookin, D., Brewster, S., and Jiang, W. (2008). Investigating touchscreen accessibility for people with visual impairments. In *Proceedings of the 5th Nordic Conference on Human-computer Interaction: Building Bridges*, NordiCHI ’08, pages 298–307, New York, NY, USA. ACM.

Meier, A., Matthies, D. J. C., Urban, B., and Wettach, R. (2015). Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2Nd International Workshop on Sensor-based Activity Recognition and Interaction*, WOAR ’15, pages 11:1–11:11, New York, NY, USA. ACM.

Meijer, P. (2016). The vOICe for Android. https://goo.gl/DDLg03.

Miller, D., Parecki, A., and Douglas, S. A. (2007). Finger dance: A sound game for blind people. In *Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets ’07, pages 253–254, New York, NY, USA. ACM.

Minatani, K. and Watanabe, T. (2012). A non-visual interface for tasks requiring rapid recognition and response: an rc helicopter control system for blind people. In *Proceedings of the 13th International Conference on Computers Helping People with Special Needs*, pages 630–635, Berlin, Heidelberg. Springer-Verlag.

Morris, M. R., Wobbrock, J. O., and Wilson, A. D. (2010). Understanding users' preferences for surface gestures. In *Proceedings of Graphics Interface 2010*, GI '10, pages 261–268, Toronto, Ont., Canada, Canada. Canadian Information Processing Society.

Moschos, M. M. (2014). Physiology and psychology of vision and its disorders: A review. *Medical Hypothesis, Discovery and Innovation in Ophthalmology*, 3(3):83–90.

Mott, M. E. and Wobbrock, J. O. (2014). Beating the bubble: Using kinematic triggering in the bubble lens for acquiring small, dense targets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, pages 733–742, New York, NY, USA. ACM.

Nacenta, M. A., Kamber, Y., Qiang, Y., and Kristensson, P. O. (2013). Memorability of pre-designed and user-defined gesture sets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 1099–1108, New York, NY, USA. ACM.

Ng, A. and Brewster, S. (2013). The relationship between encumbrance and walking speed on mobile interactions. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, pages 1359–1364, New York, NY, USA. ACM.

Ng, A., Brewster, S. A., and Williamson, J. (2013). The impact of encumbrance on mobile interactions. In *Proceedings of the 14th IFIP TC 13 International Conference on Human-Computer Interaction*, INTERACT '13, pages 92–109.

Nicolle, C. and Elton, E. (2016). Understanding everyday activities in context. http://designingwithpeople.rca.ac.uk/understanding-everyday-activities-in-context.

Oh, U., Branham, S., Findlater, L., and Kane, S. K. (2015). Audio-based feedback techniques for teaching touchscreen gestures. *ACM Trans. Access. Comput.*, 7(3):9:1–9:29.

Oh, U. and Findlater, L. (2015). A performance comparison of on-hand versus on-phone nonvisual input by blind and sighted users. *ACM Trans. Access. Comput.*, 7(4):14:1–14:20.

Oliveira, J., Guerreiro, T., Nicolau, H., Jorge, J., and GonÃ§alves, D. (2011). Brailletype: Unleashing braille over touch screen mobile phones. In *Proceedings of the 13th IFIP TC 13 International Conference on Human-Computer Interaction*, INTERACT'11, pages 100–107, Berlin, Heidelberg. Springer-Verlag.

Pamplona, V. F., Oliveira, M. M., Aliaga, D. G., and Raskar, R. (2012). Tailored displays to compensate for visual aberrations. *ACM Trans. Graph.*, 31(4):81:1–81:12.

Pareddy, S., Agarwal, A., and Swaminathan, M. (2016). Knowwhat: Mid field sensemaking for the visually impaired. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, SUI '16, pages 191–191, New York, NY, USA. ACM.

Park, K., Goh, T., and So, H.-J. (2014). Toward accessible mobile application design: Developing mobile application accessibility guidelines for people with visual impairment. In *Proceedings of HCI Korea*, HCIK '15, pages 31–38, South Korea. Hanbit Media, Inc.

Park, W. and Han, S. H. (2014). An analytical approach to creating multitouch gesture vocabularies in mobile devices: A case study for mobile web browsing gestures. *International Journal of Humanâ€"Computer Interaction*, 30(2):126–141.

Pawluk, D. T., Adams, R. J., and Kitada, R. (2015). Designing haptic assistive technology for individuals who are blind or visually impaired. *IEEE Transactions on Haptics*, 8(3).

Pielot, M., Poppinga, B., Heuten, W., and Boll, S. (2012). Tacticycle: Supporting exploratory bicycle trips. In *Proceedings of the 14th International Conference on Human-computer*

Interaction with Mobile Devices and Services, MobileHCI '12, pages 369–378, New York, NY, USA. ACM.

Pier, M. D. and Goldberg, I. R. (2005). Using water as interface media in vr applications. In *Proceedings of the 2005 Latin American Conference on Human-computer Interaction*, CLIHC '05, pages 162–169, New York, NY, USA. ACM.

Poláček, O., Grill, T., and Tscheligi, M. (2012). Towards a navigation system for blind people: A wizard of oz study. *SIGACCESS Access. Comput.*, (104):12–29.

Prasanna, P., Jain, S., Bhagat, N., and Madabhushi, A. (2013). Decision support system for detection of diabetic retinopathy using smartphones. In *Proceedings of the 7th International Conference on Pervasive Computing Technologies for Healthcare*, PervasiveHealth '13, pages 176–179, ICST, Brussels, Belgium, Belgium. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

Pressl, B. and Wieser, M. (2006). A computer-based navigation system tailored to the needs of blind people. In *In Proceedings of the 10th International Conference on Computers Helping People with Special Needs*, ICCHP'06, pages 1280–1286. Springer-Verlag.

Project-RAY (2016). Smart phones for blind, cells for visually impaired.

Qian, H., Kuber, R., and Sears, A. (2013). Developing tactile icons to support mobile users with situationally-induced impairments and disabilities. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '13, pages 47:1–47:2, New York, NY, USA. ACM.

Quek, F. and Oliveira, F. (2013). Enabling the blind to see gestures. *ACM Trans. Comput.-Hum. Interact.*, 20(1):4:1–4:32.

Rädle, R., Jetter, H.-C., Schreiner, M., Lu, Z., Reiterer, H., and Rogers, Y. (2015). Spatially-aware or spatially-agnostic?: Elicitation and evaluation of user-defined cross-device interactions. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 3913–3922, New York, NY, USA. ACM.

Rekik, Y., Grisoni, L., and Roussel, N. (2013). Towards many gestures to one command: A user study for tabletops. In *Proceedings of the 14th IFIP TC 13 International Conference on Human-Computer Interaction*, INTERACT '13, pages 246–263.

Rekik, Y., Vatavu, R.-D., and Grisoni, L. (2014). Understanding users' perceived difficulty of multi-touch gesture articulation. In *Proceedings of the 16th International Conference on Multimodal Interaction*, ICMI '14, pages 232–239, New York, NY, USA. ACM.

Rico, J. and Brewster, S. (2009). Gestures all around us: User differences in social acceptability perceptions of gesture based interfaces. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '09, pages 64:1–64:2, New York, NY, USA. ACM.

Rico, J. and Brewster, S. (2010). Usable gestures for mobile interfaces: Evaluating social acceptability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, pages 887–896, New York, NY, USA. ACM.

Rock, I. (1997). *Indirect Perception*. MIT Press.

Rock, I., Linnett, C. M., and Grant, P. (1992). Perception without attention: Results of a new method. *Cognitive Psychology*, 24(4):502–534.

Rodriguez, R., GarretÃ³n, J. Y., and Pattini, A. (2016). Glare and cognitive performance in screen work in the presence of sunlight. *Lighting Research and Technology*, 48(2):221–238.

Rotard, M., Taras, C., and Ertl, T. (2008). Tactile web browsing for blind people. *Multimedia Tools and Applications*, 37(1):53–69.

Rovner, B., Casten, R., Hegel, M., Leiby, B., and Tasman, W. (2007). Preventing depression in age-related macular degeneration. *Archives of General Psychiatry*, 64(8):886–892.

Rubine, D. (1991). Specifying gestures by example. In *Proceedings of the 18th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '91, pages 329–337, New York, NY, USA. ACM.

Sagata, Y., Watanabe, M., and Asano, Y. (2007). Voiceblog for blind and weak-eyed people. In *Proceedings of the 4th international conference on Universal access in human-computer interaction: applications and services*, UAHCI '07, pages 961–969. Springer-Verlag.

Sánchez, J. and Aguayo, F. (2007). Mobile messenger for the blind. In *Proceedings of the 9th Conference on User Interfaces for All*, ERCIM'06, pages 369–385, Berlin, Heidelberg. Springer-Verlag.

Schauerte, B., Martinez, M., Constantinescu, A., and Stiefelhagen, R. (2012). An assistive vision system for the blind that helps find lost things. In *Proceedings of the 13th International Conference on Computers Helping People with Special Needs*, ICCHP'12, pages 566–572, Berlin, Heidelberg. Springer-Verlag.

Schildbach, B. and Rukzio, E. (2010). Investigating selection and reading performance on a mobile phone while walking. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services*, MobileHCI '10, pages 93–102, New York, NY, USA. ACM.

Schmidt, A., Aidoo, K. A., Takaluoma, A., Tuomela, U., Laerhoven, K. V., and Velde, W. V. d. (1999). Advanced interaction in context. In *Proceedings of the 1st International Symposium on Handheld and Ubiquitous Computing*, HUC '99, pages 89–101, London, UK, UK. Springer-Verlag.

Schönauer, C., Mossel, A., Zaiti, I.-A., and Vatavu, R.-D. (2015). Touch, movement & vibration: User perception of vibrotactile feedback for touch and mid-air gestures. In *Proceedings of the 15th IFIP TC.13 International Conference on Human-Computer Interaction*, INTERACT '15, pages 165–172.

Schuchhardt, M., Jha, S., Ayoub, R., Kishinevsky, M., and Memik, G. (2015). Optimizing mobile display brightness by leveraging human visual perception. In *Proceedings of the 2015 International Conference on Compilers, Architecture and Synthesis for Embedded Systems*, CASES '15, pages 11–20, Piscataway, NJ, USA. IEEE Press.

Sears, A., Lin, M., Jacko, J., and Xiao, Y. (2003). When computers fade: Pervasive computing and situationally-induced impairments and disabilities. In *Proceedings of HCI International '03*, pages 1298–1302. Lawrence Erlbaum Associates.

Senra, H., Barbosa, F., Ferreira, P., Vieira, C. R., Perrin, P. B., Rogers, H., Rivera, D., and Leal, I. (2015). Psychologic adjustment to irreversible vision loss in adults: A systematic review. *Ophthalmology*, 122(4):851–861.

Shaik, A. S., Hossain, G., and Yeasin, M. (2010). Design, development and performance evaluation of reconfigured mobile android phone for people who are blind or visually impaired. In *Proceedings of the 28th ACM International Conference on Design of Communication*, SIGDOC '10, pages 159–166, New York, NY, USA. ACM.

Shen, F. (2016). Talking location. https://itunes.apple.com/us/app/talking-location/id887104200?mt=8.

Shinohara, K. and Tenenberg, J. (2007). Observing sara: A case study of a blind person's interactions with technology. In *Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '07, pages 171–178, New York, NY, USA. ACM.

Siqueira, J., de Melo Nunes, F. A. A., Ferreira, D. J., Silva, C. R. G., de Oliveira Berretta, L., Ferreira, C. B. R., FÃ©lix, da Silva Soares, A., da Costa, R. M., and Luna, M. M. (2016). Braille text entry on smartphones: A systematic review of the literature. In *Proceedings of the 2016 IEEE 40th Annual Computer Software and Applications Conference (COMPSAC)*, pages 521–526.

SmartTools (2016). Smart magnifier. https://goo.gl/9XFBTS.

Song, J., Sörös, G., Pece, F., Fanello, S. R., Izadi, S., Keskin, C., and Hilliges, O. (2014). In-air gestures around unmodified mobile devices. In *Proceedings of the 27th Annual ACM*

Symposium on User Interface Software and Technology, UIST ’14, pages 319–329, New York, NY, USA. ACM.

Statista (2016). Smartphone users worldwide 2014–2019 | statistic. http://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/.

Su, C.-H., Chan, L., Weng, C.-T., Liang, R.-H., Cheng, K.-Y., and Chen, B.-Y. (2013). Naildisplay: Bringing an always available visual display to fingertips. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’13, pages 1461–1464, New York, NY, USA. ACM.

Szpiro, S., Hashash, S., Zhao, Y., and Azenkot, S. (2016a). How people with low vision access computing devices: Understanding challenges and opportunities. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS ’16.

Szpiro, S., Zhao, Y., and Azenkot, S. (2016b). Finding a store, searching for a product: A study of daily challenges of low vision people. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, UbiComp ’16, pages 61–72, New York, NY, USA. ACM.

Szymczak, D., Magnusson, C., and Rassmus-Gröhn, K. (2012). Guiding tourists through haptic interaction: Vibration feedback in the lund time machine. In *Proceedings of the 2012 International Conference on Haptics: Perception, Devices, Mobility, and Communication - Volume Part II*, EuroHaptics’12, pages 157–162, Berlin, Heidelberg. Springer-Verlag.

Tanuwidjaja, E., Huynh, D., Koa, K., Nguyen, C., Shao, C., Torbett, P., Emmenegger, C., and Weibel, N. (2014). Chroma: A wearable augmented-reality solution for color blindness. In

Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, UbiComp ’14, pages 799–810, New York, NY, USA. ACM.

Tian, Y. and Yuan, S. (2010). Clothes matching for blind and color blind people. In *Proceedings of the 12th International Conference on Computers Helping People with Special Needs*, ICCHP’10, pages 324–331. Springer-Verlag.

Tinwala, H. and MacKenzie, I. S. (2010). Eyes-free text entry with error correction on touchscreen mobile devices. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, NordiCHI ’10, pages 511–520, New York, NY, USA. ACM.

Tomlinson, B. J., Schuett, J. H., Shortridge, W., Chandran, J., and Walker, B. N. (2016). Talkin’ about the weather: Incorporating talkback functionality and sonifications for accessible app design. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI ’16, pages 377–386, New York, NY, USA. ACM.

Tu, H., Ren, X., Tian, F., and Wang, F. (2014). Evaluation of flick and ring scrolling on touch-based smartphones. *International Journal of Humanâ€“Computer Interaction*, 30(8):643–653.

Tu, H., Ren, X., and Zhai, S. (2015). Differences and similarities between finger and pen stroke gestures on stationary and mobile devices. *ACM Trans. Comput.-Hum. Interact.*, 22(5):22:1–22:39.

Turunen, M., Soronen, H., Pakarinen, S., Hella, J., Laivo, T., Hakulinen, J., Melto, A., Rajaniemi, J.-P., Mäkinen, E., Heimonen, T., Rantala, J., Valkama, P., Miettinen, T., and Raisamo, R. (2010). Accessible multimodal media center application for blind and partially sighted people. *Comput. Entertain.*, 8(3):16:1–16:30.

Vatavu, R.-D., Anthony, L., and Wobbrock, J. O. (2012). Gestures as point clouds: A $p recognizer for user interface prototypes. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction*, ICMI '12, pages 273–280, New York, NY, USA. ACM.

Vatavu, R.-D., Anthony, L., and Wobbrock, J. O. (2013). Relative accuracy measures for stroke gestures. In *Proceedings of the 15th ACM on International Conference on Multimodal Interaction*, ICMI '13, pages 279–286, New York, NY, USA. ACM.

Vatavu, R.-D., Anthony, L., and Wobbrock, J. O. (2014). Gesture heatmaps: Understanding gesture performance with colorful visualizations. In *Proceedings of the 16th International Conference on Multimodal Interaction*, ICMI '14, pages 172–179, New York, NY, USA. ACM.

Vatavu, R.-D., Cramariuc, G., and Schipor, D. M. (2015). Touch interaction for children aged 3 to 6 years: Experimental findings and relationship to motor skills. *International Journal of Human-Computer Studies*, 74:54–76.

Vatavu, R.-D. and Mancas, M. (2014). Visual attention measures for multi-screen tv. In *Proceedings of the 2014 ACM International Conference on Interactive Experiences for TV and Online Video*, TVX '14, pages 111–118, New York, NY, USA. ACM.

Vatavu, R.-D. and Mancas, M. (2015). Evaluating visual attention for multi-screen television: Measures, toolkit, and experimental findings. *Personal and Ubiquitous Computing*, 19(5–6):781–801.

Vatavu, R.-D., Mossel, A., and Schönauer, C. (2016). Digital vibrons: Understanding users' perceptions of interacting with invisible, zero-weight matter. In *Proceedings of the 18th*

International Conference on Human-Computer Interaction with Mobile Devices and Services, MobileHCI '16, pages 217–226, New York, NY, USA. ACM.

Vatavu, R.-D. and Wobbrock, J. O. (2015). Formalizing agreement analysis for elicitation studies: New measures, significance test, and toolkit. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 1325–1334, New York, NY, USA. ACM.

Vatavu, R.-D. and Wobbrock, J. O. (2016). Between-subjects elicitation studies: Formalization and tool support. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 3390–3402, New York, NY, USA. ACM.

Vertanen, K. (2016). Counting fingers: Eyes-free text entry without touch location. In *CHI'16 Workshop on Inviscid Text Entry and Beyond*.

Vogel, D. and Balakrishnan, R. (2010). Occlusion-aware interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, pages 263–272, New York, NY, USA. ACM.

Vogel, D. and Casiez, G. (2012). Hand occlusion on a multi-touch tabletop. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, pages 2307–2316, New York, NY, USA. ACM.

Vogel, D., Cudmore, M., Casiez, G., Balakrishnan, R., and Keliher, L. (2009). Hand occlusion with tablet-sized direct pen input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 557–566, New York, NY, USA. ACM.

Voykinska, V., Azenkot, S., Wu, S., and Leshed, G. (2016). How blind people interact with visual content on social networking services. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*, CSCW '16, pages 1584–1595, New York, NY, USA. ACM.

Wall, S. A. and Brewster, S. A. (2006). Tac-tiles: Multimodal pie charts for visually impaired users. In *Proceedings of the 4th Nordic Conference on Human-computer Interaction: Changing Roles*, NordiCHI '06, pages 9–18, New York, NY, USA. ACM.

Wang, Z., Li, N., and Li, B. (2012). Fast and independent access to map directions for people who are blind. *Interacting with Computers*, 24(2):91–106.

WHO (2012). Global data on visual impairments 2010. http://www.who.int/blindness/GLOBALDATAFINALforweb.pdf.

WHO (2014). Visual impairment and blindness. fact sheet no. 282, august 2014. http://www.who.int/mediacentre/factsheets/fs282/en/.

WHO (2016). International statistical classification of diseases and related health problems 10th revision (icd-10) - who version for 2016. http://apps.who.int/classifications/icd10/browse/2016/en.

Wiese, J., Saponas, T. S., and Brush, A. B. (2013). Phoneprioception: Enabling mobile phones to infer where they are kept. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 2157–2166, New York, NY, USA. ACM.

Wimmer, R. and Echtler, F. (2013). Exploring the benefits of fingernail displays. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, pages 937–942, New York, NY, USA. ACM.

Wobbrock, J. O. (2006). The future of mobile device research in hci. In *Proceedings of the CHI '06 Workshop What is the Next Generation of Human-Computer Interaction?*, pages 131–134.

Wobbrock, J. O., Aung, H. H., Rothrock, B., and Myers, B. A. (2005). Maximizing the guessability of symbolic input. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '05, pages 1869–1872, New York, NY, USA. ACM.

Wobbrock, J. O., Kane, S. K., Gajos, K. Z., Harada, S., and Froehlich, J. (2011). Ability-based design: Concept, principles and examples. *ACM Trans. Access. Comput.*, 3(3):9:1–9:27.

Wobbrock, J. O., Morris, M. R., and Wilson, A. D. (2009). User-defined gestures for surface computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 1083–1092, New York, NY, USA. ACM.

Wobbrock, J. O., Wilson, A. D., and Li, Y. (2007). Gestures without libraries, toolkits or training: A $1 recognizer for user interface prototypes. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology*, UIST '07, pages 159–168, New York, NY, USA. ACM.

Wolf, K. and Henze, N. (2014). Comparing pointing techniques for grasping hands on tablets. In *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services*, MobileHCI '14, pages 53–62, New York, NY, USA. ACM.

Wu, S. and Adamic, L. A. (2014). Visually impaired users on an online social network. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’14, pages 3133–3142, New York, NY, USA. ACM.

Xu, C., Israr, A., Poupyrev, I., Bau, O., and Harrison, C. (2011). Tactile display for the visually impaired using teslatouch. In *CHI ’11 Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’11, pages 317–322, New York, NY, USA. ACM.

Yang, Y. and Hwang, S. (2007). Specialized design of web search engine for the blind people. In *Proceedings of the 4th international conference on Universal access in human-computer interaction: applications and services*, UAHCI ’07, pages 997–1005, Berlin, Heidelberg. Springer-Verlag.

Ye, H., Malu, M., Oh, U., and Findlater, L. (2014). Current and future mobile and wearable device use by people with visual impairments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’14, pages 3123–3132, New York, NY, USA. ACM.

Yoon, D., Hinckley, K., Benko, H., Guimbretière, F., Irani, P., Pahud, M., and Gavriliu, M. (2015). Sensing tablet grasp + micro-mobility for active reading. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST ’15, pages 477–487, New York, NY, USA. ACM.

Zhang, J., Ong, S. K., and Nee, A. Y. C. (2008). Navigation systems for individuals with visual impairment: A survey. In *Proceedings of the 2Nd International Convention on Rehabilitation Engineering & Assistive Technology*, iCREATe ’08, pages 159–162, Kaki Bukit TechPark II,, Singapore. Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre.

Zhao, S. and Balakrishnan, R. (2004). Simple vs. compound mark hierarchical marking menus. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology*, UIST ’04, pages 33–42, New York, NY, USA. ACM.

Zhao, Y., Szpiro, S., and Azenkot, S. (2015). Foresee: A customizable head-mounted vision enhancement system for people with low vision. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*, ASSETS ’15, pages 239–249, New York, NY, USA. ACM.

Zhao, Y., Szpiro, S., Knighten, J., and Azenkot, S. (2016). Cuesee: Exploring visual cues for people with low vision to facilitate a visual search task. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, UbiComp ’16, pages 73–84, New York, NY, USA. ACM.

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Figure 1: Interactions on today’s smart devices are entirely *visual* and require a direct view to locate, touch, and control on-screen objects. Eye conditions that affect vision clarity or the field of view determine less efficient and, possibly, ineffective interaction. From left to right: (a) clear sight of a mobile touchscreen device as experienced by a person with full sight; (b) peripheral vision loss, in this case caused by moderate glaucoma; (c) central vision loss, in this case caused by moderated age-related macular degeneration; (d) visual acuity loss, determined for example by hyperopia; (e) color blindness. Note: images were produced using the Vision and Hearing Impairment Simulator available on www.inclusivedesigntoolkit.com; images produced and included with permission.

Figure 2: On-the-go use of mobile devices creates many situations in which a direct, clear view of the device’s screen is not possible. Examples of causes of such temporary visual impairments, of situational nature, are: (a) partial and (b) complete screen occlusion; (c) difficulty to look at or (d) reach the mobile device; (e) screen glare. Although such situations can be easily corrected,

they make touchscreen interaction with mobile devices temporarily not available. More such situations are discussed in the paper that relate to psychological factors, device accessibility, physical environments, and social interactions.

Figure 3: Methodological approach adopted to group prior work in this survey of the state-of-the-art in touchscreen interaction and visual impairments.

Figure 4: Principal causes of visual impairment worldwide (year 2010), according to data from the World Health Organization (WHO, 2012, 2014). Uncorrected refractive errors and cataracts are responsible for 76% of all visual impairment causes, while 18% of causes are undetermined.

Figure 5: Simulations for visual acuity loss, peripheral and central vision loss, and color perception loss, caused by refractive errors, glaucoma, diabetic retinopathy, macular degeneration, and cataract in the mild, moderate, and severe conditions. Note: images were produced using the Vision and Hearing Impairment Simulator available on www.inclusivedesigntoolkit.com; images produced and included with permission.