How People with Low Vision Access Computing Devices: Understanding Challenges and Opportunities

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ABSTRACT
Low vision is a pervasive condition in which people have difficulty seeing even with corrective lenses. People with low vision frequently use mainstream computing devices, however how they use their devices to access information and whether digital low vision accessibility tools provide adequate support remains understudied. We addressed these questions with a contextual inquiry study. We observed 11 low vision participants using their smartphones, tablets, and computers when performing simple tasks such as reading email. We found that participants preferred accessing information visually than aurally (e.g., screen readers), and juggled a variety of accessibility tools. However, accessibility tools did not provide them with appropriate support. Moreover, participants had to constantly perform multiple gestures in order to see content comfortably. These challenges made participants inefficient—they were slow and often made mistakes; even tech savvy participants felt frustrated and not in control. Our findings reveal the unique needs of low vision people, which differ from those of people with no vision and design opportunities for improving low vision accessibility tools.

ACM Classification Keywords
• **Social and professional topics~Assistive technologies** • Human-centered computing~User studies • Human-centered computing~Empirical studies in accessibility

1. INTRODUCTION
Visual impairments have different manifestations and can affect seeing in a variety of ways, from a simple need for glasses, through low vision to no vision at all. Low vision is used to describe a variety of visual conditions that cannot be corrected with glasses or contact lenses and affect daily functions (e.g., Stargardt's Disease or Retinitis Pigmentosa). Low vision is pervasive, at least 3.3 million Americans over the age of 40 have low vision [34], and this estimate is expected to increase dramatically in the coming decades due to age related eye disease [7, 22]. People with low vision may have limited peripheral or central vision, blurred vision, extreme light sensitivity, or tunnel vision [6], thus their visual experiences are very different from people who have no vision.

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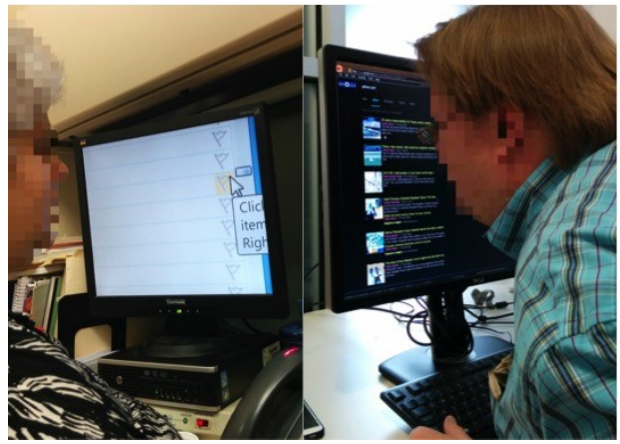

Figure 1: On the left, a participant uses Microsoft Outlook with a screen magnifier leading to two problems. First, the flag symbol appears on her screen but the corresponding email cannot be viewed simultaneously. Second, her mouse initiated a context menu that is out of view. On the right, a participant sits close to the screen because he doesn't want to use a screen magnifier; the display colors are inverted, which distorts the images.

Today, technology assumes an increasingly important role in many aspects of our lives, and accessing digital information is required for education, employment and leisure. It is thus important to minimize the digital gap in our society, especially for people with disabilities and the first step to that end is to understand what factors lead to the divide. Thus, we conducted a study that examined how people with low vision interact with their personal computing devices (smartphones, tablets, and laptop and desktop computers) when performing common daily activities such as reading an online article. Specifically, we asked how do people use their devices: *what* accessibility tools do they use, *how* do they use these tools, and *what challenges* do they face when using them.

Low vision people use a variety of mainstream computing devices such as smartphones, tablets, and e-books [9], but there has been little research on how software low vision accessibility tools are used to interact with these devices. Previous research on accessibility tools has focused on accessing print materials with low vision aids (e.g., optical lens magnifiers). Low vision aids (LVAs) are somewhat useful for low vision people [21], but many LVAs are abandoned [10]. It is unclear whether and how LVAs help access digital interfaces. There has been little research on software low vision accessibility tools. One study examined browsing with a screen magnifier and found that participants struggled to get an overview of a webpage due to the limited view of the screen magnifier [30]. Some studies examined performance on computer tasks (e.g., icon identification tasks and mouse movements) and found that low vision people did not perform well on them [18, 27, 28]. Still, it remains understudied how people with low vision access interfaces on mainstream devices (such as smartphones) and whether and how they use low vision accessibility tools.

For our study, we recruited 11 low vision participants where we observed them as they completed several common tasks on their personal computing devices (i.e., smartphones, tablets and computers) such as reading online news and writing an email. We used contextual inquiry [34] to interview and observe them in-situ. This method, in which researchers observe participants' behavior in a daily activity in real-time, allowed us to discover how people with low vision access interfaces with technology and whether and how they use accessibility tools.

Our study revealed three key findings:

1. Low vision software accessibility tools did not meet participants' needs. Participants struggled trying to constantly adjust to changes in visual content (e.g., when switching between applications or websites), but still preferred visual information to text-to-speech options.
2. Low vision software accessibility tools were difficult to use. Even though software accessibility tools required many gestures to manipulate, they did not provide enough control for participants to see content comfortably. Even proficient technology users had difficulties performing simple tasks like reading an online news article. This prevented some participants from using accessibility tools such as screen magnifiers. Moreover, the inefficiency of interacting with technology made participants feel loss of control and disorientation.
3. Participants often felt uncomfortable disclosing their disability, which also prevented them from using certain tools.

In summary, our findings illuminate the gaps between existing accessibility tools and the needs of low vision people. Our study highlights opportunities to improve the design of accessibility tools for the large and understudied low vision population.

2. RELATED WORK

2.1 Use of Low Vision Aids

Several studies found that using low vision aids (LVAs) like lens magnifiers and video magnifiers can be effective. In many cases, researchers measured the effectiveness of LVAs by asking people to read newsprint. For example, a study conducted in Britain found that LVAs significantly improved newsprint reading for low vision people [21] and a study in Finland found that 91.4% of low vision participants were able to read newsprint with low vision aids [31]. Yet, these studies only examined reading printed material with magnification in controlled lab experiments.

Although LVAs can be helpful, several studies found that they are often not used. A survey study in the U.S. found that 19% of prescribed devices were abandoned (defined as not used in the last three months) [10]. Surveys in Europe have found even larger abandonment rates. In Scotland, a third of low vision participants reported that they never used their LVAs [23] and in Britain this number was as high as 77% [16]. It remains unclear why people abandon their LVAs: while in one study abandonment of LVAs was associated with non-central vision loss, but not with age, time from prescription, or visual acuity [10], in another study decreased visual acuity and increased age were significant factors that decreased the use of LVAs [23].

One method that increases the use of LVAs is training and vision rehabilitation services. In the U.S., training and vision rehabilitation are often provided by private optometry practices and state agencies [25]. These training services can teach people how to effectively use their residual vision and how to use prescribed LVAs [24]. Training enables people to use their LVAs more effectively and was even associated with lowering depression rates [15]. However, despite the fact that rehabilitation services are helpful and available, they are not fully taken advantage of. Only 44% of ophthalmologists and 27% of optometrists referred low vision patients to rehabilitation [35], and one survey of low vision adults showed that the percent of participants receiving rehabilitation services was as low as 6% [4]. Importantly, people who receive training are more likely to use their devices. For example, in a survey of American veterans with low vision most reported receiving more than 20 hours of training and continued to use their devices frequently [32].

These studies illustrate the gaps between the availability, effectiveness, and use of LVAs, and the availability of vision rehabilitation services. Critically, these studies examined the usability of LVAs for reading print. It is unclear whether and how these aids are used for accessing computer interfaces.

2.2 Use of Technology by Low Vision People

People with low vision use technology frequently, but the patterns and challenges of their use of technology remain understudied. Electronic books have been shown to improve access to books for people with low vision [8, 9, 12]. For example, one study found that reading on digital readers, such as the iPad, was faster than reading print (with the same text size), for age-related macular degeneration patients [13]. A recent survey examined the use of electronic consumer devices by people with visual impairments, and found that most people with low vision used a smartphone and nearly half used a tablet [9]. Smartphones were used for phone calls (94% of users), text messaging (90%), email and internet (80%), and other applications (77%); tablets were used for internet browsing (100%), reading books (60%), and for using applications (54%). Most participants reported that changing the text size was the most useful function on their smartphones; unfortunately, the authors did not discriminate between methods that modify the text size, so it remains unclear how they changed fonts (by changing the font size, using pinch-to-zoom, or using screen magnifiers). Other useful functions were text-to-speech (36%), followed by using a large screen (34%), and the ability to modify contrast (30%) and font type (26%). On tablets, similar functions were indicated as useful, though to a lesser degree. Interestingly, nearly half of the participants indicated that they used the device's camera to see objects more easily, most likely as a digital magnifier. It is important to note however that in the study participants were recruited via social media and thus the sample is not representative. The authors recommend, "that device and content manufacturers consider the needs of people with vision impairment when designing and upgrading their systems," but they do not describe any specific challenges low vision people may have or make any specific recommendations about how to modify devices and applications to make them more suitable for low vision people.

Pseudo-nym	Age/ Gender	Employment	Diagnosis And Visual Acuity	Diagnosis Onset	Computing Devices
Richard	56/M	Retired programmer	Bilateral Optic Atrophy; 20/220	Birth	Samsung Galaxy 4, Windows Computer
Lora	55/F	Part time dance instructor	Steven Johnson Syndrome; left: 20/150, right: l20/200	4	Feature phone, Windows Computer
Gordon	23/M	Student; Programmer	Stargardt's Disease; Unknown	21	iPhone, MacBook Pro, Apple Watch
Joanna	55/F	Unemployed	Pathological myopia (right eye), detached retina (left eye); 20/200	25	iPhone, Sony Xperia tablet, MacBook Pro
Yasmin	68/F	Part time teacher at a senior center	No vision in the right eye; tunnel vision in the left eye; left: 20/80	55	iPhone, Windows Computer
Adam	36/M	Math Tutor	Reverse Retinitis Pigmentosa; 20/300	6	iPhone, iPad, Windows Computer
Marie	58/F	Teacher for the visually impaired	Retinopathy of Prematurity; left: 20/400; right: 20/300	Birth	iPhone, Windows Computer
Ethan	31/M	Private contractor	Albinism; 20/200	Birth	iPhone, iPad, Windows Computer
Megan	30/F	Student	Nystagmus; Unknown	Birth	LG smartphone, Windows Computer
Oprah	20/F	Student	Stargardt's Disease; Unknown	19	iPhone, MacBook Pro
Kate	59/F	Technology sales	Retinitis Pigmentosa (Usher syndrome); 20/50	50	iPhone, iPad, MacBook Pro, Apple Watch

Table 1: Participant information and devices they used.

Some studies examined the challenges of performing tasks on the computer by people with low vision. Theofanos and Redish observed how low vision participants use ZoomText [33] when browsing a U.S. government site and described several challenges participants experienced [30]. For example, participants struggled to get an overview of a webpage due to the limited view of a screen magnifier. Another challenge was that participants missed items on the screen. Menus on the right of the webpage were rarely viewed, and white space in a webpage layout caused confusion when magnified because it became huge. Some developed strategies to overcome their challenges like copying text material to a word document. The authors made several recommendations for web-design, such as not relying on color to convey information (because some users modify the color view) and checking that style sheets and fonts enlarge properly when enlarging the text size using the browser.

Several studies examined how age-related macular degeneration patients use computers. In one study the majority of participants (70.6%) used a computer at least a few times a month, mainly for using email clients, web browsing, and word processing [3]. However, using the computer was difficult for participants with age-related macular degeneration: two studies found that performance on icon identification tasks (accuracy and speed) decreased as visual function decreased [28], and that smaller and more icons on the screen made it harder to identify icons [27]. Another study examined cursor movements by people with age-related-macular degeneration and found that movement speed and velocity were lower for people with lower visual acuities, and that performance improved when targets were larger [18].

Although prior work examined some aspects of computer use by people with low vision, the challenges they experience when accessing interfaces during daily tasks remain understudied. For example, it is unclear what tools low vision people use on smartphones to access information, how they use them, and whether these tools provide appropriate support. Several publications emphasized the need for more studies that explore the needs of low vision people when using technology [5, 17]. Our goal is to address this need with the study we present here.

2.3 Stigma and Technology Use

Beyond the difficulties of using low vision aids and performing tasks on the computers, studies found that people with low vision were concerned about social stigma. Shinohara and Wobbrock studied the social factors of interaction with assistive technology faced by people of different types of disabilities (motor, hearing, and visual impairments) [29]. They interviewed three participants with low vision and found that these participants felt self-conscious about using specialized devices, because it made their disability apparent. Kane et al. studied the accessibility of mobile devices in everyday life [20]. They found that situational impairments affected the use of mobile devices on-the-go for low vision people (e.g., lighting), and also observed low vision participants modify settings on their phones to see content. A low vision participant in their study described feeling socially awkward when using an optical magnifying glass to read text on her phone. At the time of the study only two of the nine low vision participants owned a smartphone (while today this number is likely to be higher [9]). Thus, the accessibility of touch devices was not explored in depth. Moreover, while previous studies examined the social aspects of using devices, we were also interested in examining the interactions in non-social setting, what motivated or frustrated participants when using accessibility tools.

3. METHODS

3.1 Participants

We recruited 11 participants (see Table 1) from local mailing lists of low vision people and word of mouth. We conducted a brief screening interview over the phone to determine whether the volunteers were indeed low vision by asking whether they used aids that enhanced their vision. Although all participants were low vision, they had different visual conditions. It was beyond the scope of this work to study specific types of low vision in depth. Participants varied in age from 20 to 68 (mean=44.6, SD=16.8), gender (four males, seven females), employment status (four full time, five part-time or students, and two were unemployed), and technology experience (from a computer programmer to participants who used a computer only occasionally).

3.2 Procedure

Our study consisted of a two-hour session, which started with a brief semi-structured interview about participants' demographics, employment status, visual condition, and use of computing devices.

Our goal in the study was to observe how participants used their devices to access information across applications. To that end, we brainstormed common tasks people perform on their devices and used the following: find an online news article related to finance and read it aloud, find an email and write a short response, write a grocery list, send a text message, and pick an item from a take-out menu. We asked participants to perform all of these tasks on all of their devices. We did not expect participants to use specific applications because participants owned different devices and had their own preferences. If participants did not perform a task frequently or were not able to do so, we did not insist that they complete the task, because we were interested in observing tasks that participants completed routinely. For example, Richard did not read news online, and Yasmin forgot her password and could not login to her email. We also asked participants to demonstrate how they used any other frequently used applications.

While participants performed the tasks, we observed them and occasionally interrupted with questions. We encouraged participants to explain what they did and why, to understand their motivations and thought processes, following a master-apprentice relationship model of contextual inquiry [1]. We sought to identify the challenges they encountered accessing information when performing tasks: when they chose to use assistive tools, what tools they used and why (e.g., screen magnifier versus screen reader), how they used these tools (e.g., panning or modifying magnification level), how the completed the task (e.g., whether it was efficient) and how they felt performing it (e.g., frustrated).

For nine participants, the study was conducted in the lab, and for two it was conducted at their homes. We asked participants who came to the lab to bring their computing devices and if not possible (e.g., Lora did not own a computer but regularly used one at her local library) we made sure to have in the lab the assistive software they used (e.g., ZoomText).

3.3 Analysis

We audio-recorded all interviews and had them transcribed by a professional service. During the interviews, we took pictures of scenarios that illustrated participants' challenges.

We initially developed codes using open coding during data collection. After data collection was finished, two researchers independently read the transcripts and categorized the data. The researchers met periodically and discussed the coding categories (the challenges, strategies, and tools participants used). In the rare cases when coders disagreed, they discussed the issue until they reached agreement. We continued recruiting participants until we reached saturation: no new challenges or strategies were revealed.

Subsequently, the researchers developed themes using axial coding [26] and affinity diagrams [1].

4. RESULTS

Participants struggled to use technology for a variety of reasons. Except for one case, none of the participants used LVAs to access their devices; instead they used software accessibility tools. We describe specific challenges with the most frequently used accessibility tools like screen magnifiers. We also describe challenges that were evident across tools and tasks, such as knowing what tools are available or the difficulty using gestures.

4.1 Specific Challenges With Low Vision Accessibility Software

The first thing we noticed when participants used their devices is that they used many accessibility tools. We summarize the tools participants used in **Tables 2-3**, however we note that this list of tools only represents tools that were frequently used by participants and many more are available in the market. Participants also appropriated existing tools for accessibility (e.g., the phone's camera or display settings). Moreover, participants often used several tools simultaneously or switched between them depending on the task or their ability to see content. Overall, the experience of using such tools was challenging. Ethan explained the difficulty using low vision accessibility tools:

You're either stuck with reading a bunch of stuff that you just don't want to read [with VoiceOver] or you're stuck with just using all these gestures and fighting to find your position of where you want to be [with Zoom]. (Ethan)

4.1.1 Screen Magnification

Five participants used screen magnifiers on their personal computers (ZoomText, Magic, or Zoom) and three used it regularly on their touch devices (e.g., Zoom). However, participants encountered different challenges with screen magnifiers. These challenges with screen magnification led participants to struggle using them and even avoid screen magnifiers altogether. Instead, some enlarged text if possible, and all participants positioned the screen of the device very close to their eyes at some point during the study.

On computers, the main challenge with screen magnifiers was that participants had difficulty panning. Several screen magnification applications are available on computers (see **Table 3**). Users move the cursor to pan them. Participants did not like panning. For example, Adam did not use screen magnifiers at all on his computer, because of the difficulty panning; instead, he moved his head very close to the part of the screen he wanted to see (see **Figure 1**). Kate summarized why she didn't like to use Zoom on her MacBook because it was "tedious and time-consuming."

Another challenge with screen magnifiers was that the field of view was small, making it difficult to see the context and leading participants to miss items. For example, Marie tried to understand whether an email was important in Outlook. In Outlook there are flag symbols to indicate importance of emails, and they appear inline with the title of the email. However, because Marie used a screen magnifier the space between the email and the corresponding symbol became huge, which made it hard to understand which email matches which symbol (See **Figure 1)**.

Yet another challenge with screen magnifiers was that magnification was uniform across the screen regardless of content, making it difficult to navigate and understand content. For example, pictures became huge and thus hard to see. When Marie read an online news article she explained she couldn't see pictures and read the text simultaneously because the level of magnification she required for reading, makes the pictures "overwhelming," which made her feel "lost". She ended up switching back and forth between magnification levels to read the article comfortably.

Technique	Tools	Platform	Description	Designed For LV?
Magnification	Zoom	OSX	Screen Magnifier. Activated by the keyboard, panning performed with the cursor.	Yes
	Windows Magnifier, ZoomText, Magic	Windows	Screen Magnifiers. Activated by the keyboard, panning performed with the cursor.	Yes
Inverted Colors	Dark Mode	OSX	Inverts the colors of menus.	No
	Negative Colors	OSX, Windows	Inverts colors of content.	Yes
Text-to-Speech	Speak Selection	OSX	A text-to-speech option that allows users to select text to be read aloud.	No
	VoiceOver, ZoomText, Magic	OSX, Windows	A screen reader that allows the user to access content on their device with synthesized speech.	Yes

Table 3: Tools used by participants on laptop or desktop computers.

In some cases using the screen magnifier made it impossible to perform certain actions. For example, when Marie was using Outlook, she moved her cursor on an item leading a context menu to appear, but because of magnification, the menu was outside the field of view, when she panned to see the menu, she moved the cursor causing the menu to disappear (see **Figure 1**).

On touch devices (smartphones and tablets), participants either did not know about the screen magnification option, were confused about it (see section **4.2**), or struggled with panning which led them not to use it. On touch devices, panning required multiple fingers to move the view (see **Table 2**) and participants complained that that was especially cumbersome. Participants explained panning meant too much "back and forth" (Yasmin) and "was not easy to manipulate" (Oprah). Adam said he sometimes used his smartphone in landscape orientation to reduce the need for panning. Another strategy, both Adam and Ethan used on their touch devices, was to avoid using screen magnifiers when browsing by switching from mobile versions of websites to desktop versions because desktop versions allow users to pinch-to-zoom to magnify content. Many participants simply held their devices very close to their eyes instead of using a screen magnifier, though this strategy could make their disability apparent to their surrounding (see section **4.3**).

4.1.2 Inverted Colors

Inverting colors was a popular method to access text among participants. Six participants inverted colors to allow them to read text comfortably on their touch devices and one used it on the computer. However, this method inverts *all* colors on the screen regardless of content, which was not always helpful and in many cases confusing. For example, pictures were also inverted, and all participants mentioned they did not like viewing distorted pictures (see **Figure 1**). Oprah explained she even avoided using this method for that reason, "When I do the inverse thing it affects the pictures, and that bothers me. If it would just reverse the text and leave the pictures alone that would be great. I don't use it, because it freaks me out."

Another problem was that in some cases the content's style was already "inverted." Some websites were designed with light text over a dark background, causing a need to un-invert, as Kate explained:

Another trouble with inverting colors is let's say you're in one part of an app and the background is white and you've got it inverted, now I have that nice dark color but another page in the app or an app like the weather apps, uses the dark backgrounds already and you go to those, you're, "Oops! Okay I've got to hurry up and turn my inverted colors off because that one's already inverted now I have to un-invert it in order to read it". (Kate)

Switching between the "normal" and the "inverted" mode was tiring for participants. Adam explained he sometimes simply avoided switching between modes. For example, when shopping on Amazon, he only viewed the shapes of products and read the product descriptions for color information, because products pictures were inverted.

Kate, who worked in technology sales, found it difficult to communicate at work because she inverted colors on her devices, "People use color to reference things all the time. At work, it's a real problem when people go and click on the blue button while I have inverted colors, so it happens to be, orange or something." She was also disturbed that the esthetic design of a webpage changes so dramatically when colors are inverted. All the participants who used this feature expressed a desire for a "smart" invert option, which will invert text, but intelligently, making sure that only text is inverted and that the color schemes will be chosen to accommodate the needs of low vision people.

4.1.3 Text-to-Speech

Participants had mixed feelings about text-to-speech options. Although many used text-to-speech (six participants), they tended to prefer accessing materials visually. Participants explained that even though their vision is not like a sighted person, they preferred using it than converting information to audio because visual text was easier to comprehend. Lora explained that when she was taking a college course, she was only offered auditory learning materials because of her visual impairment, but she was not able to process auditory information as well as she could visually, "I need to see it to retain it. When listening to something, I couldn't absorb learning the material as quickly as I could when I was able to see it." Adam said that reading visually helps him comprehend the text and described himself, "I'm kind of a weird blind person, I'm very visual. Not that I couldn't understand it if I was listening, but it's just easier [to read visually]." Myra as a teacher for the visually impaired, said she recommends low vision students screen readers when their visual reading was so slow that they lost the meaning of the text. It is worth noting that Kate, who was hard of hearing, found it difficult to use text-to-speech options.

Although most participants preferred reading visually, six participants still used text-to-speech options, mostly on touch

Main Function	Tools	Platform	Description	Designed For Low Vision?
Magnification	Zoom, Magnifying Gestures	iOS, Android	Screen Magnifier. Activated by triple tap, panning performed with three (iOS) or two (Android) fingers.	Yes
	Pinch-to-Zoom	iOS, Android	Allows enlarging content by pinching two fingers. Works only on some applications and websites.	No
	Camera	iOS, Android	The camera can be appropriated as a magnifier to enlarge objects in the user's surroundings.	No
	Magnification Applications, KNFB Reader	iOS, Android	Applications that magnify objects in the environment using the camera. KNFB Reader converts printed text to digital text using the camera and OCR technology.	Yes
Inverted Colors	Invert Colors, Negative Colors	iOS, Android	Inverts all colors on the screen.	Yes
Text-To-Speech	VoiceOver, TalkBack	iOS, Android	A screen reader that allows the user to access content on their device based on spoken descriptions.	Yes
	Speak Selection	iOS	A text-to-speech option that allows users to select text to be read aloud.	Yes
Speech Input	Dictation	iOS, Android	A speech-to-text option that allows users to dictate text to their phone instead of typing it.	No
	Siri	iOS	A speech-to-text option that allows users to speak voice commands on the phone.	No
Font Settings	Device Settings	iOS, Android	Allows users to modify font size, font type and font boldness on built in system applications.	No
Contrast/ Brightness	Device Settings	iOS	Allows users to control display brightness and contrast.	No

Table 2: Tools used by participants on mobile devices.

devices, though three participants also used it on their computers. On touch devices, participants mainly used screen readers (VoiceOver or TalkBack), but struggled controlling them. The main problem with screen readers was that they were designed for eyes-free interaction, but our low vision participants wanted to use their vision to control them. For example, participants wanted to choose what would be read aloud, scroll through irrelevant text and read visually while listening to the speech by using Zoom or pinch-to-zoom. Another challenge was that interacting with screen readers required gestures that could not be combined with non-screen reader gestures. Thus, the screen reader gestures did not work well with other low vision enhancements gestures such as Zoom or pinch-to-zoom. In contrast to touch devices, on the computer, participants used text-to-speech, but none used screen readers, which made their interactions more efficient. Three participants used "Speak Selection" on Mac for reading long texts and Ethan used NVDA [14] on his PC, a program that allowed users to move the cursor to positions that would be read aloud.

4.1.4 Appropriating the Phone's Camera as a Magnifier

While the previous accessibility tools improved access to the device's interface, the phone's camera can improve access to the environment. Six participants appropriated the phone's camera as a digital magnifier to enlarge objects in the environment. Three participants compared the phone's camera to a portable CCTV. Participants complained about the camera's autofocus and the low resolution of the pictures. For example, Marie said she always used her magnifying lens first, because the camera goes "in and out of focus." Still, she said she liked the phone's camera because it allowed her to modify magnification while the magnification level of the magnifying glass is fixed. Ethan used a dedicated applications with OCR technology (see **Table 2**) to convert images to digital texts that can be read more easily (because fonts and colors can be adjusted) or used with text-to-speech.

4.2 Knowing What's Available

Participants' knowledge of accessibility tools varied. While some participants were proficient users of multiple accessibility tools (e.g., Ethan, Kate, Gordon), others did not know what was available or how to operate them (e.g., Marie, Oprah). Several times during the study the researcher asked about an accessibility tool, and participants wanted to be taught how to use it.

Ten participants used a smartphone daily (all participants except for Lora who owned a feature phone) , but none of our participants were trained to use their smartphones' accessibility tools. This lack of knowledge, led many to struggle using accessibility tools on their smartphone and to use their phones in general. For example, five participants did not know about the option to use a screen magnifier (e.g., Zoom). Moreover, all participants were confused at some point during the study regarding whether pinch-to-zoom can be used to magnify content (note that the screen magnifier can always be used). For example, Joanna explained she didn't use Zoom because its magnification level is limited, when in fact it's pinch-to-zoom level magnification that is limited. Yasmin, did not know about Zoom, and held an optical magnifier over her phone.

4.3 Discomfort Disclosing Oneself as LV

Participants discussed their discomfort with having people around them know they are visually impaired, since in most cases their disability was invisible. There was, however, one outlier, Adam, who was active in blind culture and occasionally used a cane, was very comfortable with his low vision identity. Except for Adam other participants' discomfort disclosing their disability affected their use of technology.

Participants felt uncomfortable modifying programs in ways that allowed them to see more easily, when it made their disability apparent in social settings. Gordon, a university student, avoided inverting colors on Microsoft Word despite the significant visual assistance it provided because he was worried it would attract attention. Instead, he would take notes in a coding editor, which is more commonly used with inverted colors, and thus did not attract attention. Moreover, Gordon also avoided increasing the font size on his computer's settings. He said, "I'm definitely a little self conscious about it, which might also be a subconscious reason I don't change as many things on my computer."

Similarly, other participants did not use certain technologies because strangers were in the vicinity. For instance, Richard did not use text-to-speech software, because he was worried what strangers would think about him, and Marie did not use her smartphone on the subway because she was worried that the magnified content would attract attention and put her at risk as a person with a disability. Participants who did use technology did so discreetly. For example, Joanna used the phone's camera to look at street signs and to recognize people approaching her, but was worried strangers would get upset if they thought she was photographing them. She used the camera covertly: "I pretend like I'm talking on the phone and not taking a picture."

4.4 Changes in Visual Experiences

One main challenge of low vision is that the visual experience of people with low vision varies across time (months or even during the day) and scenarios (e.g., lighting conditions). This challenge was amplified for our participants when using their devices, because the content on their devices changed constantly (e.g., between applications) and so their ability to comfortably see it.

Inconsistent experiences stemmed from different factors. Some were due to limited abilities of accessibility tools. For example, increasing the font in the settings of devices only affected built-in applications on the phone, and the pinch-zoom worked only on some websites. Another challenge was the variability of content itself—designs of websites can include multiple background colors, font styles and sizes. This created issues for participants, who had to adjust the zoom level and invert colors accordingly. For example, in Messages application on the iPhone the user's messages have a different background color than the messages sent by others. When inverted, the user's own messages have an orange background and black text, making it difficult to read. Gordon explained how he had to constantly switch colors to use the applications, "let's say someone sent me a text and I'm trying to read it, I'll read it, type it, invert, read it, type, invert back to normal."

4.5 Difficulty with Gestures

Participants struggled to use multiple gestures to adjust the content to see it comfortably. When using invert colors, participants often had to switch between turning it on and off, to allow them to read easily (see example in Section **4.4**). Similarly, using screen magnifiers required panning, which was especially demanding on touch devices, because it required scrolling with multiple fingers (see **Table 3**). Moreover, participants regularly switched between zoom levels according to the font size on the screen. In many cases the difficulty performing multiple gestures led participants to ignore certain content on the screen. For example, Adam did not look at photos of products because switching between the reverse colors modes to be able to read text versus seeing images was too much work, and Yasmin missed an error message because she did not pan the magnifier around the page.

Although performing gestures was difficult for participants, they wanted more options to control the interface. For example, participants who used VoiceOver wanted to be able to use their ability to see screen content to control VoiceOver and even combine it with using the Zoom simultaneously. Ethan was the only participant who used "Speak Selection" on his phone, which gave more control over what would be read out loud and was clearly an advantage, but even he still used VoiceOver occasionally. Participants also wanted to control font size and colors in menus of different applications.

4.6 Confusion and Loss of Control

Participants often felt a loss of control when they interacted with their devices. For example, when Adam used a Zoom gesture that also initiated a VoiceOver action, he said that he feels like he has a ghost in his phone. Marie, was panning on a shopping website and suddenly the product image appeared huge because her mouse cursor hovered over it. She felt disoriented: "Now I'm lost, and I don't even know how I got here."

Participants also frequently made mistakes that caused disorientation or annoyance. Adam said that needing to pan the magnifier as he read interrupted his flow. At some point when he was panning, he was confused because he accidentally clicked an ad. Similarly, Ethan clicked a popup ad by accident and then described how upsetting it can be to try and close it: "I would get so annoyed, because I would be trying to find the close button for that." These miss-clicks are noteworthy especially since both Ethan and Adam were tech savvy participants, Ethan was an IT contractor and Adam had built his own computer.

4.7 Inefficiency When Using Technology

Participants were inefficient when performing common tasks because they made errors, were slow, and did not see items on the screen. Even tech-savvy participants made mistakes by clicking on wrong items on the screen (see above, section **4.6**). Moreover, because low vision is associated with low visual acuity, it was hard for participants to see items on the screen. For example, when Lora was asked to choose an article from the finance section, she panned around the menus several times but missed the button. The difficulty seeing items made performing tasks time consuming. For example, when visiting new webpages with a screen magnifier, Lora described how she had to slowly pan around the page to learn its layout and menu locations, which made her anxious.

Software updates came up as an issue for two participants because they had to learn new interactions, but learning itself was difficult because the accessibility of the device had changed due to the update. For example, Gordon mentioned an update that changed menu items to a thin font, which he could barely see, and Kate said she prepared herself ahead of time to learn how to deal with software updates in the fall. Kate summarized the inefficiency of using low vision accessibility tools:

I can still somehow or another, with magnification, with taking a picture, with doing whatever, I can force myself to do most things. It's all about the time. It's not about whether or not there's a way to get it done, it's about how to get it all done in one day. (Kate)

5. DISCUSSION

Low vision has been described as an "invisible disability" [29] because it is not apparent to the surroundings, but it is also invisible in the sense that it lacks public awareness [19], especially in how it affects people's daily life.

Our results emphasize how different visual abilities lead to different interactions with technology. People with little to no vision use eyes-free interaction, and mostly gain information through screen readers. For example, a blind person may use Jaws [2] to interact with their PC and VoiceOver to interact with their iPhone. Although not all content will be accessible, this person would rely on a screen reader to receive auditory information and the quality of the auditory information would be similar (e.g., pitch or speed). In contrast, our participants juggled many accessibility tools that provided a variety of functionalities (see **Tables 2-3**). Although these tools helped our participants customize the visual content, participants still struggled seeing items on the screen and used multiple gestures to control their experience. Still, participants described they preferred accessing information visually than with screen readers. Our participants' challenges also emphasize the difference between people with low vision and sighted people. While people with low vision do have functional vision, it is not nearly as good as sighted people's vision (see **Table 1**). Although some of the problems our participants encountered are also common to sighted people (e.g., accidentally clicking an ad or the annoyance of software updates), the frequency and variety of the issues in conjunction with the many tools participants used illustrate the extra challenges low vision imposes on users. This made their interactions with technology inefficient and often led even tech savvy participants to feel frustrated.

Our study offers a new perspective into the use of technologies by people with low vision. Most previous research on low vision has examined low vision aids (e.g., [10, 16, 21, 23, 24, 32]), rather than low vision software accessibility tools. Only a few studies examined computer interactions, measuring the performance of only one task (e.g., icon identification [27, 28] or mouse movements [18]). One study, performed over a decade ago, examined the challenges and strategies of low vision people on a computer when browsing a government website [30]. They found that the limited field during magnification confused participants. Our study expands this result by finding additional challenges with screen magnifiers on the computer and by also examining the use of screen magnifiers on smartphones. We found that panning gestures were cumbersome and that navigation was difficult because magnification enhanced also pictures and spaces (see Section 4.1.1). Thus, our results highlight how little software accessibility for low vision has improved over the past decade, even given the advances in mobile and computer technologies.

5.1 The Need for Better Vision Enhancement

We found that although participants used many tools, existing tools did not provide adequate support for their needs. On the one hand, existing vision enhancement tools provided ineffective support. All our participants required some level of magnification on their devices, but they struggled using screen magnifiers. Participants found panning difficult and confusing, had to constantly change magnification levels and miss-clicked items. Similarly, color inversion, used by many, provided only limited support because it inverted all colors and thus distorted images and did not help when content was already inverted. On the other hand, screen readers were not a good solution for our participants. Screen readers rely on eyes-free interactions, but our participants stressed they wanted to control screen readers by using visual information. For example, they wanted to use their vision to choose what would be read aloud and to be able to listen to speech while reading visually. However, combining screen magnification gestures with VoiceOver gestures was confusing and hard to manipulate correctly. Furthermore, the majority of participants explained they relied on vision for comprehension, so text-to-speech options did not address all their needs.

These challenges illustrate the need to improve the usability of low vision tools. For example, participants desired smarter color inversion tools that would always provide dark background and light text. Participants also wanted more options to customize text on applications, such as the ability to choose color, background and font size. They also wanted to be able to modify settings across all applications, instead of only on system applications. Improving panning gestures is critical for users to adopt screen magnifiers, especially on touch devices. Participants did not like using multiple fingers for panning, and found the interaction with pinch-to-zoom much easier, probably because it only requires one finger to move the view. Website designers should consider allowing pinch-to-zoom to operate on mobile website versions or at least allow users to switch to desktop website versions so users can use pinch-to-zoom.

Another issue our participants faced was a constant need to adjust to different visual designs. Future research should examine the possibility of using machine learning to learn user's visual abilities and adapt content automatically. For example, systems can infer what font sizes users can see comfortably by capturing users' interactions, possibly in combination with eye tracking. Users may also have similar use patterns, and those could also be learned automatically. Automatic adjustment of content to abilities of users has been shown to be useful [11], and has the potential to benefit also low vision users.

5.2 Training and Discoverability

Prior research showed that training services improved the use of LVAs [32]. Our study further illustrates the importance of such training. For example, none of our participants were trained on using accessibility tools on their smartphones. As a consequence, participants did not know about screen magnifiers on the phone, confused screen magnifiers and pinch-to-zoom, and struggled controlling screen magnifiers. Because smartphones are widely used by low vision people [9] (as also evident in our study), it is important that vision services also teach how to use touch devices in addition to LVAs and computer programs. In addition, designers should also consider the discoverability and usability of accessibility tools.

6. LIMITATIONS

Our goal was to study software accessibility tools on mainstream devices using common tasks like reading email. However, there are additional scenarios that should be explored in future research, such as software tools used at the workplace. We asked participants to use their devices to add ecological validity to our study, but that also limits our results to devices participants owned. Future research should address the challenges of tools and devices that participants may not be familiar with.

7. CONCLUSIONS

In this paper, we presented findings from a study designed to understand the challenges people with low vision face when accessing interfaces on their computing devices. We found that participants faced challenges using accessibility tools, mainly because tools did not provide adequate support for their needs. While accessibility tools required many gestures, they did not provide enough control for participants to see content comfortably. Our study also illustrated how people with low vision rely on their vision to comprehend information, and their need for more sophisticated vision enhancement tools. Our work provides opportunities for future research for an important and ignored user group.

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