Understanding Low Vision People's Visual Perception on Commercial Augmented Reality Glasses

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ABSTRACT
People with *low vision* have a visual impairment that affects their ability to perform daily activities. Unlike blind people, low vision people have functional vision and can potentially benefit from smart glasses that provide dynamic, always-available visual information. We sought to determine what low vision people could see on mainstream commercial augmented reality (AR) glasses, despite their visual limitations and the device's constraints. We conducted a study with 20 low vision participants and 18 sighted controls, asking them to identify virtual shapes and text in different sizes, colors, and thicknesses. We also evaluated their ability to see the virtual elements while walking. We found that low vision participants were able to identify basic shapes and read short phrases on the glasses while sitting and walking. Identifying virtual elements had a similar effect on low vision and sighted people's walking speed, slowing it down slightly. Our study yielded preliminary evidence that mainstream AR glasses can be powerful accessibility tools. We derive guidelines for presenting visual output for low vision people and discuss opportunities for accessibility applications on this platform.

Author Keywords
Accessibility; augmented reality; user study; low vision.

ACM Classification Keywords
H.5.1. Information interfaces and presentation: Multimedia Information Systems

INTRODUCTION
According to the Centers for Disease Control and Prevention (CDC), 3.3 million Americans who are 40 years old and older have low vision. A person has low vision if she has a visual impairment that adversely affects her ability to perform daily activities and cannot be corrected with glasses or contact lenses. People with low vision can have a variety of visual conditions, including reduced contrast sensitivity, loss of visual field, and lower visual acuity [3]. Since most diseases or conditions causing low vision occur as people age, the number of low vision people is expected to increase drastically as the population ages [2].

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Since low vision cannot be corrected with standard eyeglasses or contact lenses, some researchers have developed applications for smart glasses [23,29,47]. Most of these applications, along with some commercial products, were developed for video see-through (VST) platforms, which capture the user's view with a camera, modify it, and present it on a digital display that is mounted on the user's face. For example, eSight [10] are video see-through smart glasses that allow the user to magnify and adjust the contrast of her field of view. Smart glasses have the advantage of being always-available and hands-free. Video see-through platforms are particularly powerful since they can modify the user's vision directly with a variety of image processing algorithms.

Recently, many optical see-through (OST) smart glasses platforms have entered the marketplace, such as Google Glass, Microsoft Hololens, and the Epson Moverio. In contrast to VST platforms, OST smart glasses project light over the user's vision and allow users to see the real world with their natural vision [50]. They incorporate virtual elements into the physical world, which prevents a feeling of disorientation often experienced with VST glasses. However, OST glasses have distinct limitations. The range of image processing techniques that can be performed on the user's view of the world is more limited than with VST platforms. For example, the user's view cannot be magnified and black-on-white print cannot be reversed to white-on-black. The user's field of view is more restricted than it is with some VST platforms [38,48]. Since many low vision people have reduced contrast sensitivity, low acuity, or loss of field of view, it is unclear how they perceive the virtual elements on current OST AR glasses and whether they could use and benefit from these glasses.

Considering the limitations of OST smart glasses along with their potential advantages, we sought to determine whether and what low vision people could see on these glasses. Augmented reality applications are designed for different environments, both in- and outdoors [7,15] and today's OST devices strive to be lightweight and comfortable to facilitate continuous and long-term wear. In line with the pervasive computing vision, OST glasses are designed for use throughout the day while the user is engaged in other activities [15,34]. Effective use of the devices while walking or engaging in other activities poses another potential barrier to low vision users. Studies found that low vision people expend a higher cognitive load while walking, which may affect their ability to visually process the displayed content [30,41]. To understand low vision people's perceptual abilities on OST glasses in various activities, we aim to explore what and how they could see on these glasses in both stationary and mobile scenarios.

We address the following research questions in this paper:

1. What is low vision people's visual ability (visual acuity and contrast sensitivity) when perceiving virtual elements on OST smart glasses as opposed to physical elements?
2. What kinds of virtual elements can low vision people perceive on OST glasses in a stationary setting? What virtual elements (in terms of size, thickness, shape, etc.) *can* they see and what elements do they *prefer*?
3. What is low vision people's ability to perceive virtual elements on OST smart glasses in a mobile setting? How do the glasses hinder their walking speed and how does walking affect their visual perception of elements on the glasses?

It is important to examine low vision people's perceptual abilities on a *mainstream* commercially-available smart glasses platform as opposed to a specialized device. Aside from the potential of smart glasses in general—which have already been established by prior work in the area—using mainstream devices as accessibility tools has many advantages over specialized devices, including significantly lower cost, availability, and social acceptability. Unsurprisingly, specialized devices like the eSight ($15,000) cost more than mainstream devices because they target a significantly smaller market and cannot leverage economy of scale. Studies have shown repeatedly that people with disabilities often feel stigmatized by specialized devices [24,33], which can lead to abandoning the device altogether [32].

In summary, this paper contributes a study that demonstrates the potential of commercial optical see-through AR glasses for low vision users and provides guidelines for researchers and developers who seek to develop accessibility applications for low vision people.

RELATED WORK

We describe related work from three directions: (1) vision enhancement systems on video and (2) optical see-through glasses, as well as (3) studies that aim to understand low vision people's visual perception.

Video See-Through Vision Enhancement

Video see-through smart glasses are an appealing solution for low vision users. These systems can completely manipulate the user's view of the world instead of just projecting light onto it. For example, VST smart glasses can magnify the input video by a large factor [38,48]. They can also magnify a portion of the user's view [48] or possibly distort their view to avoid a blind spot [34]. Virtual elements on VST displays can be seamlessly integrated into the user's view of the real world [50].

VST smart glasses have been studied and developed as an accessibility aid for low vision people for decades. Massof et al. designed the Low Vision Enhancement System (LVES) [22,23], a VST head-mounted binocular display with three video cameras, on which image enhancement algorithms could be implemented to improve low vision people's ability to recognize faces [27] and perform other daily tasks. Therfelder et al. [39] conducted experiments with the LVES with 25 low vision participants who completed near-distance vision viewing, reading, and writing tasks. Sixteen participants showed an improvement in task performance with the LVES system. Weckerle et al. [45] evaluated the LVES with 17 participants with central scotoma (a blind spot) who performed reading, writing, and walking tasks with the LVES., yielding some positive results for all tasks. The authors concluded that the LVES might be appropriate for tasks that require use of the hands or high magnification levels (more than 8x) that are not easily found with optical tools. Harper et al. [14] also discussed the benefits and weaknesses of the LVES and a similar VST HMD called the V-Max. They claimed the systems were powerful tools that enabled low-vision people to magnify and reverse the contrast of their vision, which can improve their ability to see. However, these devices cover the users' eyes, which can cause motion sickness and disorientation. They are also heavy and can be difficult to configure [14]. Moreover, they are designed specifically for low vision people (i.e., not a mainstream device), which may lead to a high cost and device abandonment [32].

Our prior work presented ForeSee [48], another VST head-mounted display that enhances low vision people's vision. It was prototyped with commodity hardware, including an Oculus Rift DK2 and a webcam. ForeSee had five vision enhancements and two display modes, which were evaluated in an extensive study with 19 low vision participants. We described how participants with different visual impairments customized the enhancements to optimize their visual experience for viewing near- and far-distance materials, showing that participants had unique preferences for vision enhancements.

ForeSee and LVES resemble an accessibility product called eSight [10], which costs $15,000. It has several enhancements that can be adjusted by a separate control device with several buttons. eSight's nearly prohibitive cost exemplifies the disadvantages of specialized assistive technologies for people with disabilities.

Optical See-Through Vision Enhancement

Optical see-through glasses are another AR platform that has drawn researchers' attention. Researchers have studied two approaches to vision enhancement on OST smart glasses designed for mainstream use in the early 2000's (e.g., the MicroOptical Integrated EyeGlass [37])

[20,28,42,43]. These two approaches involved using edge detection algorithms to identify the contours of the scene and presenting them over the user's natural view. For people with reduced contrast sensitivity, the contours of the scene were displayed over the user's natural view of the scene to accentuate details [25]. For users with tunnel vision, a minified representation of the scene's contours were superimposed over the high-resolution area of the user's residual vision to enable her to access information from the original scene along with contours of the objects beyond her field [43]. Vargas-Martin and Peli [42] evaluated multiplexing, as they call this technique, with two participants with tunnel vision who tried the technique while walking indoors and outdoors. The results showed that the multiplexing technique doubled their visual field.

More recently, several vision enhancement techniques have been designed for Google Glass, a platform that generated excitement from a mainstream consumer base. Hwang and Peli [16] implemented their contour enhancement method for people with age-related macular degeneration who have reduced contrast sensitivity. They conducted a preliminary study with three sighted people and found the system improved their contrast sensitivity. Tanuwidjaja et al. [36] designed Chroma, an application that highlights or shifts certain colors by projecting filtered colors on the OST display. They evaluated Chroma with 23 participants with color vision deficiency who were tasked with identifying colors in different contexts. They found that Chroma improved color identification in over half the tasks on average. Itoh and Klinker [17] proposed a method to correct out-of-focus images by projecting a compensating image on a see-through display and implemented a preliminary system. However, there's no study with real users to evaluate the system performance.

While prior research focused on developing or evaluating a specific vision enhancement technique (e.g., Peli [26,42]), our work aims to understand what kinds of virtual elements low vision people can see on an OST display.

Low Vision People's Visual Perception

Researchers have conducted experiments to understand how different factors (e.g., color, font) affect low vision people's visual perception [5,44,46]. For example, Wurm et al. [46] explored the effect of color on low vision people's ability to recognize objects by conducting a study with 16 low vision participants who recognized 84 color and gray-scale food images on a digital screen as quickly and accurately as possible. They found color sped up object recognition for low vision people.

Multiple studies aimed to understand low vision people's ability to read, a challenging and important task. Legge et al. [19] compared people's reading speed for text with different luminance and color contrast (differences in chromaticity) with eight sighted and 10 low vision people, and found that, while sighted people had similar reading speeds for high color and luminance contrast, low vision people read faster with high luminance contrast than color contrast. Mansfield et al. [21] studied the effect of font on reading performance for both sighted and low vision people. They measured the reading acuity, reading speed, and the critical print size (the smallest print size that people could read with the maximum speed) for 50 sighted and 42 low vision people with text in Times (proportionally spaced) and text in Courier (fixed-width) at a 40cm distance. Results showed that, while sighted people had a higher reading speed with Times, low vision people had better reading performance with Courier for all three measures.

Researchers have also explored low vision people's walking performance and visual perception in mobile scenarios [6,12,13,18]. For example, Black et al. [6] evaluated the mobility of eight participants with retinitis pigmentosa (RP) and nine sighted controls who walked along a 57.5m pathway with a glare source, a step and ramp, and 55 randomly positioned obstacles. They instructed the participants to walk comfortably along the pathway twice under high and low luminance, finding that people with RP had worse mobility than sighted people, especially under reduced luminance. Leat and Lovie-Kitchin [18] explored the relationship between low vision people's visual ability and their mobility by measuring 35 low vision participants' walking speed in both indoor and outdoor environments with obstacles. They also measured people's visual detection distance by asking participants to stop as soon as they detected an obstacle. The study showed that walking speed has a strong correlation with participants' uncorrected useful field of view, while the visual detection distance is best predicted by people's clinical measures (e.g., contrast sensitivity).

While prior work has focused on low vision people's perception of physical objects in the world, our work presents the first known examination of how low vision people perceive virtual elements on OST smart glasses.

METHOD

We conducted a study with 20 participants with different visual conditions, evaluating their ability to see virtual elements on the Epson Moverio BT-200 glasses. We chose this platform because it has relatively advanced features for a mainstream device. Compared with Google Glass, for example, the Epson Moverio provides a larger projection area in the center of both the user's eyes, so it is likely easier for many low vision people to use.

Participants

We recruited 20 low vision participants (P1–P20) and 18 sighted participants (S1–S18) as a control. The low vision participants included nine males and 11 females, with a mean age of 45 (range: 21–69). They had a variety of visual impairments, as shown in Table 1. We required that participants have "low vision," and that participants' visual acuity should be less than or equal to 20/100. Eighteen out of the 20 participants completed the whole user study.

ID	Age/ Sex	Diagnosis	Legally Blind?	Visual Acuity (self reported)	Visual Acuity (measured)	Visual Field	Color Vision	Light Sensitivity
P1	25/F	Achromatopsia	Yes	20/400	20/400	Full	Have issues with subtle colors	Very sensitive
P2	21/F	Glaucoma	Yes	Left: no vision, right: 20/400	Over 20/400	Only on the left bottom of the right eye	Good	Not sensitive
P3	27/F	Glaucoma	Yes	20/400	Over 20/400	Very limited	Good	Very sensitive
P4	28/M	Retinitis Pigmentosa	Yes	20/100	20/400	Tunnel vision, 6-8 degrees	Have issues with subtle colors	Not sensitive
P5	34/M	Retinal detachment	Yes	Left: 20/300-20/400, right: no vision	20/400	Very limited in left eye at left bottom	Have issues with subtle colors	Very sensitive
P6	60/F	Retinitis Pigmentasa, Usher Synderome	Yes	Left: 20/100-20/200, right: 20/400	20/126	5 degrees or less	Color blindness	Very sensitive
P7	38/M	Retinitis Pigmentasa	Yes	20/300	20/320	Full	Have issues with subtle colors	A little sensitive
P8	56/F	Stevens-Johnson Syndrome	Yes	Left: 20/150, right: only has light perception	20/320	Very limited	Good	Very sensitive
P9	53/M	Central scotoma	Yes	Left: 20/200, right: 20/400	20/250	Full	Good	Very sensitive
P10	28/M	Retinblastoma	Yes	Left: not sure, prescription is plus 15, right: no vision	Over 20/400	Full on left eye	Have issues with subtle colors	Not sensitive
P11	69/F	Glaucoma, Detached retinas	Yes	Left: 20/325-20/400, right: only light perception	20/200	Tunnel vision	Have issues with subtle colors	Very sensitive
P12	64/M	Congenital cataracts	Yes	Left: 20/200, right: prosthesis	Over 20/400	Full on left eye	Good	A little sensitive
P13	32/F	Congenital Cataracts (removed), Aphakia, Nystagmus, Glaucoma	Yes	20/200	20/200	Very limited	Good	Very sensitive
P14	69/M	Glaucoma, Cataracts	Yes	Left: no vision, right: 20/200-20/250	20/80	Full on left eye	Good	Very sensitive
P15	61/F	Scar tissue at the back of both eyes, have stigma	Yes	20/400	20/400	Full	Good	A little sensitive
P16	63/F	Retinopathy of Prematurity	Yes	Over 20/400	20/400	Limited	Have issues with subtle colors	Sometimes sensitive
P17	32/M	Bardet Biedl Syndrome	Yes	Left: worse than 20/200, right: better than left	20/320	Full	Slight color blindness	Very sensitive
P18	60/F	Retinopathy of Prematurity	Yes	Left: 20/400, right: 20/300	20/250	Full	Good	Very sensitive
P19	32/M	Prematurity of Retinas, Nystagmus	Yes	20/200	20/400	Full	Good	Very sensitive
P20	45/F	Retinitis Pigmentosa	Yes	Not sure	Over 20/400	Limited	Have issues with subtle colors	Very sensitive

Table 1. Demographic information of the 20 low vision participants. We report two measures of visual acuity: the acuity reported by the participants ("self reported") and that measured during our study ("measured"). All other information about participants' visual conditions was self-reported.

P20's visual condition was too low to complete all the tasks and we lost part of P19's data. We recruited the sighted controls from our university campus. They included nine females and nine males, with a mean age of 24 (range: 22–28). Low vision participants were compensated $20 an hour and sighted participants $10 an hour.

Procedure

The study consisted of one lab session that lasted about 90 minutes. The session included three parts: assessing participants' vision using clinical measures, assessing their perception of virtual elements on the smart glasses while seated, and assessing their perception of virtual elements on the glasses while walking. Before scheduling the study, we conducted a phone screen to verify that the participants had functional vision by ensuring they used vision enhancement tools such as magnifiers on a regular basis.

TASK1: Obtaining Vision Measures with Virtual Elements

The lab study began with an assessment of participants' visual acuity and contrast sensitivity, two standard visual function tests, using real and virtual charts. The goal of this task was to obtain a standard baseline measure for visual performance with virtual elements on the glasses.

As is standard, both tests were performed by asking the user to read letters from charts that are displayed at a fixed distance from the participant. We used an ETDRS R logMAR chart to measure visual acuity [11] and a Pelli-Robson chart to measure contrast sensitivity [31] (see Figure 1). We hung both charts three meters away from the participants and measured their vision accordingly. After performing each test with a physical chart, we performed it on a virtual chart of the same size that was projected on the smart glasses at the same distance (Figure 2).

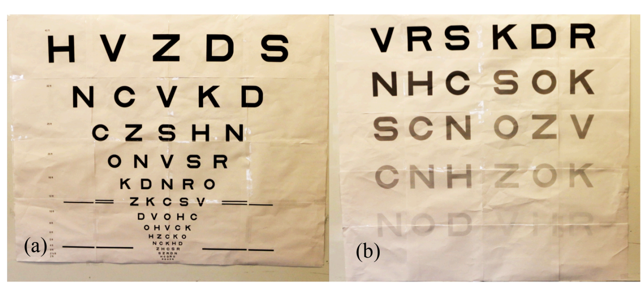

Figure 1. Standard eye charts in the study: (a) an ETDRS R logMAR chart to measure visual acuity; (b) a Pelli-Robson chart to measure contrast sensitivity.

Figure 2. Virtual eye charts: (a) an ETDRS R logMAR chart: 20/400, 20/200, 20/136 from left to right; (b) a Pelli-Robson chart: 0.05, 0.4, 1.4 in log contrast sensitivity from left to right.

TASK2: Identifying Virtual Elements in a Stationary Setting

Next, we asked participants to identify shapes and text on the smart glasses while they sat comfortably in a chair (Figure 3a). The goal of this task was to explore people's perception of visuals on the AR glasses and to determine optimal parameters for displaying virtual elements.

We displayed different sets of shapes and phrases (Table 2) on a transparent background and varied their size, color, thickness, and, for text, font. Participants could look around to change the physical environment (whiteboard/black walls), which served as the background for the virtual elements to optimize their visual experience. We explored each parameter by varying the specific parameter as we held the others constant. We used the size threshold—the smallest size that participants could identify virtual elements (at least four out of five) to measure people's visual ability for different parameters [40]. We followed the procedure below to explore the large space of parameter combinations:

1. We showed a participant a shape in the largest size and the default color (white) and thickness (medium). We asked the participant to identify the shape.
2. We gradually decreased the size of the shape, randomly choosing a shape each time. We asked the participant to identify the shape at each size until the participant can no longer identify it.
3. We kept the current shape size and displayed random shapes in different colors. For each color, we gradually decreased or increased the size until we found the smallest perceivable size in that color.
4. We set the color of the shape to white again. For each thickness, we adjusted the size of the shape until we found the smallest perceivable size for each thickness.

We repeated the same procedure for text, finding the smallest perceivable size for different colors, thicknesses, and font faces.

TASK3: Identifying Virtual Elements in a Mobile Setting

In the final task, we assessed participants' perception of virtual shapes and text on the optical see-through AR glasses in a mobile situation. The goal of this task was to determine how well participants were able to use the AR glasses in a mobile setting.

Participants identified virtual objects while walking along a 20-foot path (Figure 4). We first asked participants to choose their preferred parameter values for perceiving shapes and text. We then asked them to walk down the track in three conditions: (1) identifying shapes on the AR glasses, (2) identifying text on the AR glasses, and (3) walking without the AR glasses as a baseline. In the first two conditions, we projected the shapes or text on the glasses with the participant's preferred parameter values at a random time between one and four seconds after the participant started walking. We asked participants to comfortably walk (Figure 3b) and also verbally identify the virtual shapes or text that appeared as soon as possible. Participants walked in their usual manner: if they typically used a cane or a guide dog, we asked them to use it in the study. All participants were able to walk independently. Participants completed five trials for each condition. We projected one randomly selected shape or phrase in each trial. We counterbalanced both the order of using and not using the AR glasses and the order of identifying shapes and text.

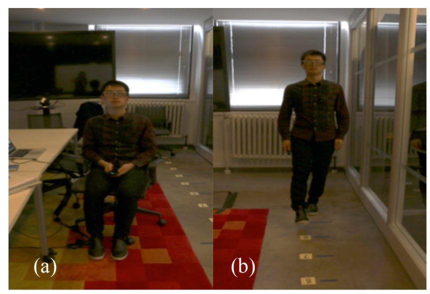

Figure 3. A participant using the AR glasses in (a) a stationary setting and (b) a mobile setting.

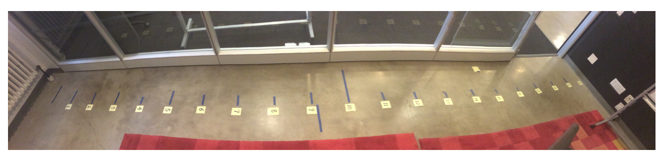

Figure 4. The 20-foot walking path labeled with Post-It notes.

Apparatus and Materials

We used the Epson Moverio BT-200 AR glasses [8], which had a 960x492 pixel display. The display size was 48 inches at a 3-meter distance. The study was conducted in a well-lit conference room in an office building. Below we elaborate on the materials used for each of the three tasks.

TASK1. We printed a standard-size ETDRS R logMAR chart [11] and a Pelli-Robson chart [31] (Figure 1). The logMAR chart measures visual acuity (ranges from 20/10 to 20/400 at 3-meter distance) by showing rows of letters in decreasing size, while the Pelli-Robson chart measures contrast sensitivity (log contrast sensitivity ranges from 0.05 to 2.3) by displaying letters in increasingly lighter shades of gray. A score of 2.0 on the Pelli-Robson chart indicates normal contrast sensitivity.

We generated the same virtual digital eye charts on the smart glasses in the same size as the physical charts at a 3-

meter distance (Figure 2). The perceived screen size of the Epson glasses changes with the user's point of view: 40" at 2.5m and 320" at 20m [9]. In the study, the perceived screen size of the glasses is 48" at 3m. We placed a whiteboard at a 3m distance and asked participants to use it as the background when reading the virtual chart, ensuring the perceived virtual chart is on a 48" screen at 3m. We measured the size of the letters on the physical charts, calculated the ratio between the letter size and the glasses screen size, and rendered the virtual letters with this ratio to generate the same size of virtual charts. Since the size of the glasses screen is limited, we presented the virtual charts line by line to the participants. With respect to brightness, Epson glasses have 20 levels of brightness. We used the default brightness (level 7) for the virtual charts to understand people's visual ability in a common setting.

TASK2. We displayed shapes (circles, squares, and triangles) and text (9 different phrases, e.g., turn left, dessert menu) with different parameters (size, color, thickness, and font for text) on the Epson BT-200 glasses. The parameters and corresponding values are listed in Table 2. We chose these basic shapes and common phrases since they could be useful in potential applications (e.g., a navigation app). Participants were able to use a whiteboard or a black wall as a background when viewing the virtual elements. Figures 5-8 demonstrate examples of a triangle shape and a phrase "Turn Left" with different colors, thickness levels, and fonts on black and white background.

TASK3. We used a well-lit meeting room (about 21 feet long) and labeled a 20-foot walking path with Post-It notes. We put Post-It notes on the floor at every foot along the walking path and each note was labeled with its distance from the starting point (Figure 4). These notes helped us record and analyze participants' walking speed.

Figure 5. A triangle with different colors on black and white backgrounds.

Figure 6. A triangle on black and white backgrounds with different thickness levels: Thin, Medium, and Thick

Figure 7. Text with different colors on black and white backgrounds. We use "Turn Left" as an example.

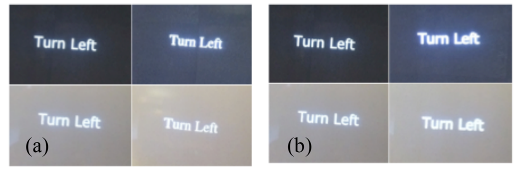

Figure 8. Text on black and white backgrounds with (a) different fonts: Verdana and Times New Roman, and (b) different thickness levels: Regular and Bold.

Analysis

We video recorded the study with a video camera that was mounted on a tripod in the experiment room. During the walking tasks, a second researcher walked beside the participant, video-recording their feet with a handheld camera as they stepped down the marked walkway. We calculated the walking time and the time participants spent recognizing virtual elements from these videos.

We analyzed the impact of OST glasses on low vision people's visual ability. We had one factor, *Condition* (*NoGlass*, *WithGlass*), and two measurements, *VisualAcuity* and *ContrastSensitivity*. We used a t-test to determine whether the change in people's visual ability between wearing and not wearing the glasses was significant. Since some low vision participants' visual acuity is out of the range of the eye chart (i.e., under 20/400, see Table 3), we used 20/500 to represent their visual acuity in the t-test.

We explored the impact of the AR glasses on people's walking time. We defined a *Trial* (1-5) as one walking task. The experiment had one within-subject factor, *Condition* (*NoGlass*, *GlassShape, GlassText*) and one measure: *WalkTime.* Since looking at different kinds of virtual elements (shapes and text) may have a different impact on people's walking speed, we compared the conditions of GlassShape and GlassText with the baseline NoGlass separately using ANOVA. We confirmed that WalkTime was normally distributed (p<0.01) with a Shapiro-Wilk test.

To validate counterbalancing, we added another between-subjects factor, *Order* (two levels: *NoGlass-WithGlass*, *WithGlass-NoGlass*), into our model. We used ANOVA to model the impact of Condition and Order on WalkTime with *Participant* as a random effect for both low vision and

	Type	Size	Color	Thickness	Font
Shape	Triangle, Circle, Square	Range: 10 - 500 pixels Step Size: 10 pixels	White (255,255,255), Yellow (255,255,0), Red (255,0,0), Blue (0,0,255), Green (0,255,0)	Thin: 5 pixels Medium: 10 pixels Thick: 15 pixels	N/A
Text	"Dessert Menu", "Lunch Special", "Danger", "Bus Stop", "Turn Left", "Restaurant", "Restroom", "Go Straight Forward", "Obstacles in Front"	Range: 10 - 500 pixels Step Size: 10 pixels	White (255,255,255), Yellow (255,255,0), Red (255,0,0), Blue (0,0,255), Green (0,255,0)	Regular, Bold	Verdana, Times New Roman

Table 2. Parameters of shapes and text on the AR glasses and their corresponding values.

sighted participants. We found no significant effect of Order on the walking time for both low vision (looking at shape on the glasses: $F_{(1,16)}$=0.01, p=*n.s.*; text: $F_{(1,16)}$=0.07, p=*n.s.*) and sighted participants (shape: $F_{(1,16)}$=3.16, p=*n.s.*; text: $F_{(1,16)}$=2.53, p=*n.s.*).

We compared low vision people's and sighted people's performance in recognizing virtual elements in terms of time. Our experiment had one between-subjects factor, *VisualCondition* (*LowVision*, *Sighted*) and two measures, *SeeShapeTime*, *SeeTextTime*. We used a t-test to determine whether there was a significant difference in the time that low vision and sighted people spent recognizing virtual elements on the AR glasses.

We also analyzed the relationship between low vision people's visual acuity and the time it took them to recognize virtual elements while walking. We used 20/200 and 20/400 as thresholds to separate low vision participants into three groups. We chose these thresholds based on visual impairment categories [4]: a person whose visual acuity is less than 20/400 has profound low vision, between 20/200 and 20/400 has severe low vision, while better than 20/200 has mild or moderate low vision. We had one between-subjects factor, *VisualAcuity* (*Low*, *Medium*, *High*) and two measures, *SeeShapeTime* and *SeeTextTime*. We used ANOVA to analyze the effect of VisualAcuity on the time that participants took to recognize virtual shapes and text during the walking task.

Since we made two comparisons (time to see the virtual elements and walking time) in each walking trial, we set the threshold of p-value as 0.025 with a Bonferroni Correction.

RESULTS

Visual Acuity on the AR Glasses

We compared people's visual acuity (VA) on the physical and virtual charts. We found that while sighted participants' visual acuity significantly decreased when looking at the virtual eye chart (t_{17}=-7.17, p<0.001), there's no significant difference in visual acuities for low vision people when using the smart glasses (t_{19}=-1.29, p=*n.s.*).

Among the low vision participants, six had a lower visual acuity on the virtual chart, four had a higher visual acuity on the virtual chart, and six had the same visual acuity when using the physical and virtual charts. Four participants could not see any lines on the eye charts, so we couldn't measure their acuity changes (see Table 3). Participants reported different visual experiences when viewing the virtual chart. Nine participants (45%) felt it was easier to see the virtual letters since they were brighter, sharper, and more contrasting. "There's more contrast between the background and the letter, and maybe it's brighter" (P6). Six participants (30%) thought the virtual letters were blurrier than those on the physical charts or too bright to see. The other five (25%) did not perceive a difference between the two charts.

Contrast Sensitivity on the AR Glasses

We compared each participant's contrast sensitivity on the physical and the virtual eye charts. We found that although sighted participants' contrast sensitivity significantly increased on the virtual chart (t_{17} = -21.49, p<0.001), low vision participants' contrast sensitivity varied on the virtual chart (t_{18}=-1.53, p=*n.s.*).

The change in contrast sensitivity was inconsistent for the low vision participants when using the physical and virtual charts. Seven participants' contrast sensitivity decreased with the virtual chart, while 11 participants' contrast sensitivity increased (Table 4). One reason that may have caused participants' contrast sensitivity to decrease is the semi-transparency of the OST glasses. When using the AR glasses, the "black" text on the white-background chart was transparent, reducing the contrast between the text and the white background. Some participants' comments also confirmed this, "They [the letters] look light on white [background], and also a little bluish" (P15).

Seeing Virtual Elements in a Stationary Setting

White and Black Backgrounds

When looking at virtual elements on the AR glasses, all low vision participants preferred a black background rather than a white background. Even when the shapes or text were displayed in dark colors (red or blue), they still felt there was more contrast between the virtual elements and the black background. P14 mentioned, "They are clearer and sharper on black. I could see more details and my eyes are more relaxed." Since the virtual elements are generated by light on the AR glasses, they usually have high luminance contrast with a dark background (e.g., black), leading the participants to see more. This aligns with prior work [19]

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
VA	20/400	<20/400	<20/400	20/400	20/400	20/126	20/320	20/250	20/320	<20/400	20/200	20/400	20/200	20/100	20/320	20/400	20/400	20/250	20/200	<20/400
VA in AR	<20/400	<20/400	<20/400	<20/400	20/320	20/126	20/320	20/320	20/250	<20/400	20/200	<20/400	20/200	20/80	20/400	20/400	20/320	20/250	20/400	<20/400

Table 3. Visual acuity (VA) with and without AR glasses for low vision participants. Since the highest level of visual acuity we could measure with the ETDRS R eye chart is 20/400, we use '<20/400' to denote the situation that the participant cannot see the first line on the eye chart.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
CS	0.95	0.8	0.5	0.5	0.35	0.8	0.35	0.95	0.8	0.35	0.95	0.5	1.1	1.1	1.1	0.2	0.05	0.95	0.5	NA
CS in AR	0.8	0.5	0.35	0.2	0.8	0.5	0.95	1.1	1.4	0.65	1.1	0.5	1.55	1.55	0.8	0.35	0.2	0.8	0.8	NA

Table 4. Contrast sensitivity (CS) with and without AR glasses for low vision participants. A score below 1.5 suggests a contrast sensitivity impairment. P20 could not see the letters with the highest contrast level due to her very severe visual condition.

that concluded that luminance contrast is more effective than color contrast for people with low vision.

Shapes

We report participants' perception of virtual shapes with different colors and thicknesses.

Color. When changing colors for low vision participants at a fixed thickness (medium), we found that white and yellow were usually the best colors, with which people could see the smallest shapes. Red was a difficult color for low vision participants to see and some participants (e.g., P2, P8, P17) needed a red shape to be much larger to identify it. Some participants could not identify any shape in red no matter how big it was (e.g., P6, P10). All participants agreed that red was too dark.

Surprisingly, although most participants felt blue was dark and hard to see on the AR glasses, four participants (P13, P15, P16, P19) liked it. They said blue had high contrast with the black background and attracted their attention well. "White and yellow were a little light. Blue has more contrast and it attracts my attention" (P15).

Thickness. When adjusting the thickness for shapes at a fixed color (white), we found that a thick border helped low vision participants identify shapes more easily. Seven people saw better when the thickness was adjusted to a thicker level. They believed that the thick border defined the shape better, "I could take a lot more shapes when it was thick" (P10). Only P1 needed a larger size threshold to identify the shapes when they were in the thickest level. She felt the shapes were filled in when they were small but had thick border, which increased the difficulty of recognizing the shape. As she mentioned, "I distinguished a shape according to its corners and its center. Now it's too thick and the center was filled." The other participants did not feel that thickness affected shape recognition.

Text

We report the impact of different parameters on participants' ability to read text on the AR glasses.

Color. With a fixed thickness (regular) and font (Verdana), we adjusted the color of the different phrases and found that white was the best color for all participants and had the smallest size threshold among all the color conditions. Some participants (e.g., P15, P16) felt that blue attracted their attention as it did when viewing shapes, but it was difficult for them to identify blue text. "I could see the text in blue but could not make out what it is" (P16).

Thickness. When comparing the two thickness levels for text (regular and bold), we found that the impact of thickness on people's ability to see text on the AR glasses varied for different low vision people. Five participants read regular text at smaller sizes while seven read smaller text when it was bold. The remaining eight participants' ability to read text was not affected by the text thickness.

Font. With a fixed color (white) and thickness (regular), we explored the impact of font on low vision people's ability to read text on the AR glasses. Our results showed that participants could usually see text in smaller sizes when the font was sans-serif because the thickness of the strokes was more consistent and there was more space between letters allowing participants to see the text more clearly. This is in line with the print standard for people with low vision [1]. The difference between the smallest perceivable size for sans-serif and serif ranged from 10 to 30 pixels, except for P10 who read text at 270 pixels with a sans-serif font but needed a 390-pixel size to read with a serif font.

Parameter Preferences

Participants reported their preferences for each parameter for viewing basic shapes and text on the AR glasses clearly and comfortably, as shown in Table 5 and Table 6. We found that most participants (75% for shapes and 85% for text) preferred a relatively large size (over 100 pixels in height). Interestingly, some participants (e.g., P1, P4) preferred the thickest border or bold text, even though they had smaller size thresholds with other thickness levels. P1 said, "it's hard to see [the shape] when it's small and bold, but when it's bigger, I preferred the thicker one." While almost all participants chose white for reading text, some preferred different colors for shapes; for example, P14 chose green and P15 chose blue.

Using the AR Glasses in a Mobile Setting

The Impact of AR Glasses on Walking Time

When analyzing participants' walking time, we found that low vision people walked significantly slower than sighted people did when not wearing glasses ($F_{(1,178)}$=37.99, p<0.001). The mean time it took low vision people to walk 20 feet was 6.71s (SD=1.15s), while the mean time for sighted people was 5.75s (SD=0.93s). This confirmed the

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Size	180	300	200	300	300	60	120	100	60	240	100	200	100	100	180	180	220	80	80	NA
Color	W	Y	W	W	W	W	W	W	Y	W	W	W	W	G	B	W	W	W	W	NA
Thickness	15	15	15	15	10	15	15	10	10	15	15	15	15	10	15	15	15	10	10	NA

Table 5. Low vision participants' preferences on size, color, and thickness when looking at shapes on the glasses. We use W, Y, R, B, G to represent white, yellow, red, blue, and green. Since P20 has ultra low vision, she did not complete this part of the study.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Size	200	500	460	220	250	120	130	150	160	500	80	170	120	60	260	260	300	110	140	NA
Color	W	Y	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	NA
Thickness	B	R	B	B	B	R	B	R	R	B	B	B	B	R	B	R	B	B	B	NA
Font	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	NA

Table 6. Low vision participants' preferences on size, color, thickness, and font when looking at text on the glasses. We use R, B in the thickness row to represent Regular and Bold; V, T in the font row to represent Verdana and Times New Roman.

result from a prior study that people with retinitis pigmentosa traveled more slowly than sighted people [12].

The participants performed walking trials with the AR glasses in two conditions: a) recognizing shapes on the AR glasses, and b) recognizing text on the AR glasses. We compared participants' walking time in these two conditions to a baseline, their walking time without the AR glasses. Our goal was to explore the impact of seeing different virtual elements on people's walking time.

We used ANOVA to analyze the data. When comparing participants' walking time when recognizing shapes on the glasses (*GlassShape*) versus walking without glasses (*NoGlass*), we found that both low vision and sighted people walked significantly slower when recognizing shapes on the AR glasses (low vision: $F_{(1,16)}$=15.07, p=0.001; sighted: $F_{(1,16)}$=13.82, p=0.002). When recognizing shapes, sighted people's walking time increased 6.6% (*GlassShape*: mean=6.13s, *SD*=0.83s; *NoGlass*: mean=5.75s, *SD*=0.93s), while low vision participants' walking time increased 9.8% (*GlassShape*: mean=7.37s, SD=1.24s; *NoGlass*: mean=6.71s, *SD*=1.15s). This showed that, compared with sighted people, recognizing shapes on AR glasses had a similar negative impact on low vision people's walking process.

We analyzed the effect of recognizing virtual text on people's walking time (*GlassText* vs. *NoGlass*) with ANOVA and also found a significant effect of Condition on WalkTime for both low vision ($F_{(1,16)}$=15.61, p=0.001) and sighted participants ($F_{(1,16)}$=18.59, p<0.001). When recognizing text on the AR glasses, sighted people's walking time (mean=6.30s, *SD*=0.91s) increased 9.6%, while low vision people's walking time (mean=7.51s, *SD*=1.24s) increased 11.9%. This indicated that identifying text on AR glasses had a similar negative effect on sighted and low vision people's walking time.

In summary, if a sighted person can use the AR glasses while walking, it is also feasible for a low vision person to use the glasses while walking.

Time to Recognize Virtual Elements

For each participant, we measured the average time that elapsed between the time the virtual element was presented and the time the participant verbally identified it. A t-test showed that the low vision participants needed significantly more time to identify text on the AR glasses than sighted people did when walking ($t_{22.31}$=4.69, p<0.001), while the time spent by low vision and sighted people recognizing shapes was not significantly different ($t_{22.65}$=2.26, p=0.034>0.025 with Bonferroni Correction). We also compared the time difference between recognizing shapes and text for low vision participants with a t-test, finding that low vision people spent a significantly longer time recognizing text than shapes (t_{17}=-4.24, p<0.001). Thus, low vision participants recognized shapes faster (their performance was more like sighted people's performance) than text. This implies that simple shapes would be preferable to text in visual UI design of AR glass applications for people with low vision.

Impact of Visual Acuity on Recognizing Virtual Elements

We explored the relationship between low vision people's visual acuity and their ability to recognize virtual elements on the go. Using ANOVA, we found a significant effect of *VisualAcuity* on the time to recognize text for low vision participants ($F_{(2,87)}$=9.25, p<0.001), indicating that people with severe visual impairments spent significantly more time than those with mild low vision recognizing text on the AR glasses. However, there was no significant time difference in recognizing shapes among people with different visual acuities ($F_{(2, 87)}$=1, p=*n.s.*). This suggests that simple shapes could be used in applications for the general low vision population, but text may only be appropriate for people with mild to moderate low vision.

DISCUSSION

Our study answered our three research questions (see Introduction) about how low vision people perceive virtual elements on a mainstream commercial AR glasses. On a high level, we demonstrated that a commercially-available mainstream optical see-through AR glasses platform has the potential to benefit people with low vision. In our study, low vision participants were able to identify shapes and read text on the AR glasses. Text and shapes are basic visual output elements that can convey a wide variety of information in different contexts. Moreover, we showed that although using the AR glasses increased low vision people's walking time, its impact on low vision people's walking was similar to that of sighted people, providing preliminary evidence that low vision people could benefit from AR applications in mobile settings just like sighted people can. Our findings indicate that low vision people could benefit from accessibility applications designed specifically for low vision, but also from mainstream applications with appropriate adjustable configurations.

When assessing participants' visual ability, we found that low vision people's visual acuity for virtual elements was not predicted by their acuity on the standard physical chart. Sighted participants all had a lower acuity for virtual elements, perhaps because of the display's limited resolution or improper fit of the device. For our low vision participants, however, visual acuity sometimes increased and sometimes decreased for the virtual charts, suggesting that the limited resolution of the display was not necessarily a problem. This suggests that participants' visual acuity on a physical chart should be considered, but not used strictly to predict performance on virtual elements.

Through our study, we found that some features of optical see-through platforms may affect low vision people's visual ability when using the AR glasses. For example, the semi-transparency of the OST glasses reduced the contrast between white text and a black background (the white text did not appear as pure white and the black background was transparent), making the text hard to read for some low vision people. Participants needed to find a solid dark background to see the virtual contents, but an ideal background may not be easy to find in a real-life scenario, while, for example, walking outside. Additionally, gaze switching between the virtual elements and the physical world could also introduce additional difficulties. However, most participants were positive about their experience using the AR glasses. Some participants (e.g., P8, P14, P18) said that they could switch their gaze between the virtual and physical world (e.g., the Post-It notes on the ground and the virtual elements) easily.

We distil our findings into several guidelines for designing virtual elements that are accessible to low vision people on the Epson Moverio and similar AR glasses.

- ***Type.*** The basic shapes were easier to identify than text. Shapes are suitable to use for the general low vision population, while text only fit for people with mild to moderate low vision. This implies that such shapes should be leveraged to convey information in applications for low vision people.
- ***Color.*** Displaying shapes and text in white, yellow, or green is much better than displaying them in red. Blue could be used to attract some low vision people's attention, but is not suitable for presenting text or detailed information.
- ***Size.*** For people who had moderate or severe low vision, virtual elements should be presented in a size that is larger than 100 pixels. Text should be presented in sans-serif fonts, which can be perceived in smaller sizes than serif fonts, enabling applications to display a phrase or short sentence on the glasses.

Based on these guidelines and the capabilities of mainstream AR glasses, we propose opportunities to design applications that provide low vision people access to information that they cannot see in the real world:

- ***Reading Inaccessible Text.*** A lot of text in real-life scenarios is inaccessible for low vision people, for example, text that is far away (e.g., street signs) or too small for people to see (e.g., medication labels). We could design AR applications that use OCR (optical character recognition) technology to extract text from the environment and display it on the glasses in an accessible way (e.g., big size with high contrast).
- ***Visual Search.*** Looking for a target from a selection of distractors is challenging for low vision people, for example, finding a friend in a crowd, or searching for a product on a grocery store shelf [35]. We propose to design applications, which recognize the target (e.g., object, face) with computer vision techniques and display simple shapes or text on the glasses screen as visual cues [49] to label and attract the user's attention to the target.
- ***Navigation.*** Way-finding is another challenge for people with low vision [35]. We could design navigation applications on AR glasses that extract geographical information with GPS and provide visual navigation and orientation cues with arrows or other basic shapes to guide users to a target location.

Our study was exploratory, aiming to answer broad research questions. We have set the stage for future studies that answer more focused research questions addressing participants with certain kinds of visual conditions, or perception tasks in certain lighting conditions (e.g., outdoors, at night). Other future studies could explore low vision people's visual perception of more complex virtual elements, such as a map, or people's performance when using AR glasses while walking in an unfamiliar or crowded environment.

CONCLUSION

In this paper, we explored low vision people's perceptual abilities on mainstream commercial optical see-through glasses by conducting a user study with 20 low vision participants and 18 sighted controls. We explored their visual perception of shapes and text on the AR glasses in both stationary and mobile settings. Our study provided preliminary evidence that low vision people could benefit from commercial OST AR glasses, especially when designers follow the guidelines we provided for displaying visual information. We hope our work will motivate researchers and designers to design AR applications for the large and growing group of low vision people, enabling them to be more productive and independent.

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