ForeSee: A Customizable Head-Mounted Vision Enhancement System for People with Low Vision

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ABSTRACT
Most low vision people have functional vision and would likely prefer to use their vision to access information. Recently, there have been advances in head-mounted displays, cameras, and image processing technology that create opportunities to improve the visual experience for low vision people. In this paper, we present *ForeSee*, a head-mounted vision enhancement system with five enhancement methods: Magnification, Contrast Enhancement, Edge Enhancement, Black/White Reversal, and Text Extraction; in two display modes: Full and Window. ForeSee enables users to customize their visual experience by selecting, adjusting, and combining different enhancement methods and display modes in real time. We evaluated ForeSee by conducting a study with 19 low vision participants who performed near- and far-distance viewing tasks. We found that participants had different preferences for enhancement methods and display modes when performing different tasks. The Magnification Enhancement Method and the Window Display Mode were popular choices, but most participants felt that combining several methods produced the best results. The ability to customize the system was key to enabling people with a variety of different vision abilities to improve their visual experience.

Categories and Subject Descriptors
H.5.1 [**Information Interfaces and Presentations**]: Multimedia Information Systems – *artificial, augmented, and virtual realities*; K.4.2 [**Computers and Society**]: Social Issues – *Assistive technologies for persons with disabilities*

Keywords
Accessibility, Visual Impairment, Augmented Reality Glasses, Vision Customization

1. INTRODUCTION
There are roughly 19 million people in the United States who have difficulty seeing when performing daily activities, even with corrective contact lenses or glasses [9]. Meanwhile, the National Federation of the Blind reports that there are only about 1.3 million legally blind people in the US [30]. This means that there are millions of people who have functional vision and would probably like to leverage their vision for performing daily activities more efficiently and comfortably. There has been a wealth of research on people with vision disabilities in the technology and disabilities community. However, most of this research ignores the residual vision that many people have and focuses on solutions with audio or vibrotactile interaction (*e.g.*, [11,23,54]). More research is needed to understand low vision people's abilities and preferences and innovate methods that will enhance people's visual experience [22].

We seek to seize an opportunity to improve accessibility for people with low vision using head-mounted display systems, an emerging mainstream technology. In the last few years, a variety of companies have developed head-mounted display systems for augmented reality [13,18,28] and virtual reality [33,44] applications, and simply as a way of having an always-available digital display [18,47]. These systems often include embedded cameras and other sensors. They have received attention from the press [53], consumers, industry, and researchers and will likely continue to develop and become widely adopted and more socially acceptable. As with mass-market technology, they will be relatively affordable and available to consumers, unlike specialized assistive technology [24,42,43]. As such, we believe head-mounted display systems can become effective, versatile, and practical accessibility tools, on which we can design dynamic customizable systems that directly enhance people's vision.

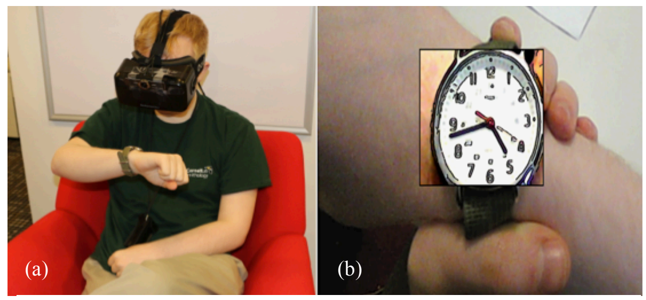

Figure 1. (a) A low vision person using ForeSee to check the time. (b) He sees an enhanced version of the watch using magnification, contrast enhancement, and edge enhancement in ForeSee's Window Display Mode.

We present *ForeSee*, a head-mounted vision enhancement system that enables people to customize their visual experience to better access information in their environment. ForeSee (Figure 1) is a video see-through augmented reality system that consists of an embedded processor, a camera, and a display that rests over the user's eyes. The camera captures the user's view, the processor enhances the captured video feed, and the display presents the enhanced video feed to the user. ForeSee has five enhancement methods: *Magnification*, *Contrast Enhancement*, *Edge Enhancement, Black/White Reversal*, and *Text Extraction*; and two display modes: *Full Display Mode* and *Window Display Mode*, which apply the enhancement to the full field of view or only to a region within the view. The user can customize their experience with ForeSee by selecting combinations of enhancement methods in either display mode and adjusting parameters of enhancement methods and display modes. Unlike prior work [36,52], ForeSee is designed to work with commodity hardware and enable users to

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create a customizable viewing experience that is best suited to their eye conditions and a given environment or task.

We conducted a user study with 19 participants with a variety of visual abilities to evaluate ForeSee's effectiveness. Participants used ForeSee to complete two visual tasks: reading a page of printed text and reading and describing textual signs that were hung above eye-level at a distance of about three meters. We chose these tasks because they represent important daily living challenges for low vision people [10]. Participants tried all of the enhancement methods and display modes during each task.

Our key findings include: (1) ForeSee's customization function had a major improvement on the users' visual experience, (2) different users preferred different combinations of enhancement methods and display modes in different viewing tasks, and (3) Window Display Mode was beneficial to most users, helping them concentrate, multitask, and understand the context of their visual target.

In summary, this paper has two main contributions:

1. *ForeSee*, a customizable head-mounted vision enhancement system for people with low vision.
2. An extensive evaluation of ForeSee, which sheds light on the effectiveness of different enhancement methods and display modes for people with different visual abilities performing near- and far-distance viewing tasks.

2. RELATED WORK

Even though the vast majority of people with visual impairments have functional vision, there has been little research studying the challenges low vision people face and innovating vision enhancement tools. Jacko and Sears [22] advocated for the importance of research on designing systems for low vision people in 1998 emphasizing the lack of innovation in the area. However, common low vision tools such as CCTV's [25], optical magnifiers, and screen magnification software [1,3,4,5,17,29] remain largely the same as they were over 17 years ago.

The development of cameras, head-mounted displays, and image processing technology has created opportunities for low vision research. There has been some prior research on head-mounted systems for low vision people. Researchers have focused on correcting specific low vision conditions. Optometry researchers have contributed several projects [26,37,38,39,40,45,52] on different head-mounted systems and algorithms to enhance the vision of people with different eye conditions. For example, Peli [37] presented a head-mounted system with a one-dimensional analog video processing algorithm for people with reduced contrast sensitivity to provide them more detailed real-time gray scale video with lower cost, weight, and power consumption. This system was evaluated by Peli and Woods [40] with 19 participants with central field loss who were tasked with recognizing celebrity faces. Forty-two percent of the participants showed significant improvement with this system. Their lab also developed a method [52] for optical see-through displays that aims to expand people's field of view by overlaying the contours of a minified view of a wide field over the center of the user's original vision. They evaluated their method with (only) two participants with Retinitis Pigmentosa who completed visual field tests with this enhancement method on head-mounted displays. They found that the participants' field of view was effectively expanded.

Instead of developing custom hardware platforms, some researchers have recently created enhancement tools for Google Glass [18]. For example, Tanuwidjaja *at el.* developed Chroma [50], a system that projects a filtered image in the Google Glass display that highlights or changes certain colors to make them discernable to a user with color blindness. They evaluated this system with 23 colorblind participants who performed color identification tasks in different contexts. In over half the tasks, Chroma improved participants' performance. Hwang and Peli [21] implemented two edge enhancement algorithms based on positive and negative Laplacian filters on Google Glass to increase contrast for people with age-related macular degeneration (AMD). They conducted a preliminary study with three sighted participants by measuring their contrast sensitivity, finding that their contrast sensitivity improved when using this system.

Besides different eye conditions, researchers have also aimed to address challenges for low vision people in specific scenarios. For example, some researchers focused on mobility. Everingham *et al*. [15] developed a neural-network classification algorithm for a head-mounted device that segmented scenes rendered in front of users' eyes and recolored objects to make obstacles more visible. Hicks *et al.* [20] built a real-time head-mounted LED display with a depth camera to aid navigation by detecting the distance to nearby objects and changing the brightness of objects to indicate their distances. In addition to mobility, some research systems and products have been developed to assist low vision people with reading. Merino-Gracia *et al.* [27] proposed a real-time text recognition algorithm for a head-mounted device with audio feedback that aims to help blind people read. However, they only measured the performance of the detection algorithm on a particular image dataset, and did not conduct a user study to evaluate its effect on blind people. A similar product on the market called OrCam [34] is a portable device with a camera but no display that is mounted on the frame of a user's eyeglasses. OrCam recognizes text and products and provides audio feedback with a bone-conducting earpiece.

Even though different head-mounted systems and enhancement methods were developed, they were mostly designed for specific low vision conditions or scenarios. Our work aims to enhance people's vision directly, with a head-mounted system that is customizable in real-time to improve accessibility for people with different visual conditions in a variety of daily tasks. One commercial product called eSight [14] includes some similar features to ForeSee. eSight is a custom head-mounted video see-through display that costs $15,000. It supports magnification, contrast enhancement and color adjustment of a real-time video-feed. But unlike ForeSee, it only provides three basic enhancement methods and does not support combinations of enhancement modes or different Display Modes. To our knowledge, eSight has not been formally evaluated with low vision users.

In addition to the novel design of ForeSee, we also present a qualitative user evaluation to gain a deep understanding of the use of different enhancement methods on a head-mounted system. We found that most evaluations of previous head-mounted vision enhancement systems involved quantitative studies like measuring speed and accuracy in search tasks (*e.g*., [15,26]). There has been little focus on the visual experience and user behavior with different enhancement methods and under different scenarios. Researchers have repeatedly shown that involving consumers in low vision assessments could reduce device abandonment [12,42,46], so researchers should involve participants in the evaluation of their systems as well, understanding their preferences and experiences. In this paper, we describe a study with different low vision people based on ForeSee to collect more comprehensive data, and summarize the users' preferences and use patterns of different enhancement methods. This work helps us understand how different enhancement methods serve different low vision conditions in different scenarios, thereby providing insights for the future design and evaluation methods of head-mounted vision enhancement systems.

3. THE DESIGN OF FORESEE

3.1 Design Guidelines

In our design exploration stage, we formulated the following guidelines to direct our design.

DG1. Enhance Vision Directly

We wanted to develop a system that enables people with low vision to use their residual vision for performing daily tasks. Meanwhile, we sought to seize an opportunity to use computer vision technology, which is able to perform various real-time transformations to video feeds, to enhance people's vision directly in all their daily living activities, without being highly task specific [19].

DG2. Use Standard Enhancement Techniques

As a starting point, we wanted to use standard enhancement methods that were already widely used and accepted by low vision people. It would be easier for users to adjust to such familiar techniques on a new platform.

DG3. Enable Customization according to Users' Preferences

We wanted our system to be customizable to suit users' needs and preferences. We believe this is especially critical for a technology that targets low vision people, since there are many different kinds and degrees of vision impairments [2]. Moreover, people's visual abilities frequently change over time and in different settings [30] (*e.g.*, a sunny sidewalk or a dimly-lit restaurant).

DG4. Enable Fast and Natural Interaction

As mentioned in DG3, people's visual abilities vary in different environments so they may need to adjust the system often. Moreover, people may need different settings for different tasks, such as reading a newspaper and looking for a friend in a crowd of people. As such it is not only imperative for the system to be customizable, but the user must be able to efficiently interact with the system in different situations to customize it.

3.2 System Description

ForeSee is a video see-through [6] augmented reality head-mounted device that is designed to work with commodity hardware. It consists of a display, a camera, and a processor. ForeSee captures a video feed of the user's surroundings from the user's point of view, sends the feed to the processor, and then displays the processed feed on the display. There is only one camera, so the user sees the world in two dimensions (in the future we may experiment with using two cameras to achieve a stereo 3D effect). The processor enhances the image in various ways, as described in Section 4.3. Unlike Google Glass, the display covers the user's entire field of view. This allows us to enhance the user's field of view directly, following DG1.

ForeSee enhances the user's vision by applying some combination of *enhancement methods* in different *display modes*. An enhancement method is a kind of transformation that is applied to the captured video feed. A display mode is a way of incorporating the transformed content into the original captured video. In its current state, ForeSee includes five enhancement methods and two display modes. Following DG2, we developed the enhancement methods and the display modes by examining commonly-used low vision aids and techniques for improving the visibility of printed and digital materials for people with low vision, as discussed in Section 2.

Currently, we created two display modes (Figure 2): ***Full Display*** and ***Window Display***. The Full Display Mode simply applies enhancement methods to the user's entire field of view. The Window Display Mode applies enhancement methods to a rectangular area within the user's field of view, shown in the bottom left corner of Figure 2. The user can change the width, height, and position of the rectangle. We modeled the Window Display Mode after a handheld magnifier. It also resembles the "lens" mode in many screen magnifiers where a rectangular area around the cursor is magnified [1,29].

We created five enhancement methods (Figure 2):

Magnification. Since magnification seems to be the most common vision enhancement method on both optical and digital devices, we created a Magnification Enhancement Method where the user can adjust the level of magnification. The magnification

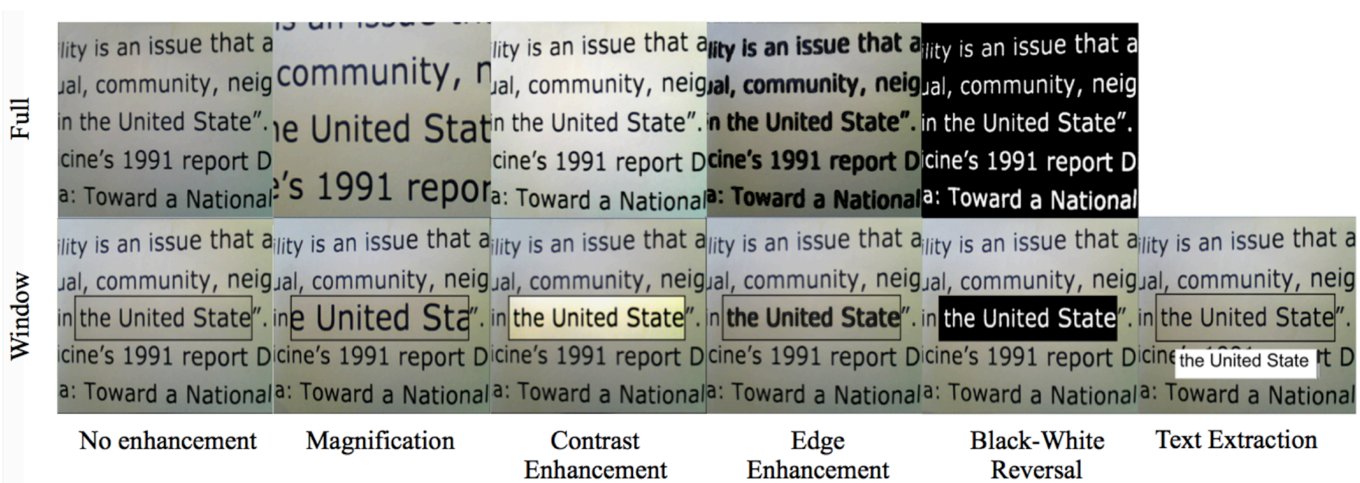

Figure 2. The visual effects of five enhancement methods: Magnification, Contrast, Edge Enhancement, and Black/White Reversal; in two display modes: Full Display Mode and Window Display Mode

Table 1. Demographic Information of the 19 Participants

ID	Age/Sex	Diagnose Result	Visua Field	Acuity	Colo Vision	Tool Used
P1	23/M	Nystagmus	Full	20/120	Good	Bifocal, telescope, software magnifier, zoom-in (magnification) on computer
P2	29/F	Optic Atrophy	Full	20/400	Could distinguish primary colors	Cane, black/white reversal on computer
P3	45/F	Pituitary gland optic nerve tumor	Limited	Unknown, but good	Good	ZoomText, CCTV, magnifier for brief reading tasks
P4	53/M	Stargardt's Disease	Full	Left: 20/800 Right: 20/600	Have color vision but not good at subtle colors	CCTV, handheld magnifiers, handheld telescopes
P5	21/F	Leber's Congenital Amaurosis	Very limited	20/600	Have color vision but not good at subtle colors	Braille notetaker, Jaws, iPhone with VoiceOver, zoom-in (magnification) to see images
P6	34/F	Retinitis Pigmentosa	Limited; 30 degrees in each eye	Unknown, but good	Good	ZoomText, cane at night
P7	34/F	Pathological Myopia; Detached retina in left eye; has cataract	Full	20/200	Have color vision but not good at subtle colors	Screen magnifiers for phone and tablet, speech input and Siri, ZoomText, color reversal
P8	56/M	Bilateral optic atrophy; Nystagmus	Full	20/220	Have color vision but not good at subtle colors	Screen magnifier, black/white reverse
P9	57/F	Usher's syndrome, Retinitis Pigmentosa	Very limited, < 5 degrees	Left: < 20/170 Right: no vision	Need high contrast to see colors	CCTV, color reversal
P10	34/F	Retinitis Pigmentosa	Limited	20/60	Color blind	Magnifier, flash light at night
P11	40/F	Detached retina	Full	Right: blind Left: 20/60	Have color vision but not good at subtle colors	Reading glasses, cane, iPhone with VoiceOver, Laptop with Zoom, CCTV
P12	65/M	Central areolar choroidal sclerosis	Unknown	Unknown	Need high contrast to see colors	CCTV, ZoomText (magnification and speech)
P13	58/F	Retinopathy of prematurity	Full	Left: 20/400 Right: 20/300	Need high contrast to see colors	Handheld monocular, CCTV, handheld magnifier, ZoomText (magnification and speech), large print
P14	51/F	Cytomegalovirus Retinitis	Very limited	Right: blind Left: unknown	Color blind	Jaws, ZoomText
P15	64/F	Retrolental Fibroplasia	Very limited	Right: unknown Left: blind	Have color vision but not good at subtle colors	Cane, screen readers (used to use magnification)
P16	55/F	Steven Johnson Syndrome	Very limited	Right: 20/200 Left 20/150	Good	Magnifier, CCTV
P17	23/M	Stargardt's Disease	Full	Limited, but unknown	More issues with contrast	Screen magnifier, color reversal
P18	36/M	Reversal class of Retinitis Pigmentosa	Full	20/300	Cannot distinguish colors of low contrast	Screen magnifiers, screen readers, color reversal
P19	68/F	Retinal myopathy, glaucoma (possibly other conditions)	Left: limited Right: almost none	Left: unknown (but limited) Right: only light perception	Cannot distinguish colors of low contrast	ZoomText, CCTV, color reversal, handheld magnifiers, iPhone with Zoom and Siri

ranges from 1 (no magnification) to 35 times the original image size in 17 increments.

Contrast Enhancement. In this method we increase the contrast of the video feed but maintain the color hues. We used a standard contrast enhancement algorithm that can be found in Szeliski [49] on page 103. We increased both the luminance contrast and color contrast by setting the RGB values of each pixel with a multiplication of 2 and an addition of -100. We then clamped the values to the standard range of [0-255].

Edge Enhancement. This method darkens and thickens the edges (or contours) in the color video stream. We used Canny's edge detection algorithm [8] to detect the edges in an image and then darkened the pixels on and surrounding the edges in the original image by setting those pixels to black. The thickness of the edge is 5 pixels.

Black/White Reversal (BWR). In this enhancement method, we used Otsu's Thresholding Method [36] to convert the video to binary (only black and white) with the threshold of 100, and then reversed the colors. People often use this type of effect (white text on a black background) when reading with CCTVs [25].

Text Extraction. This method is only available in the Window Display Mode. It detects the position of the text with the Scene Text Detection [32] in the OpenCV library [34], recognizes the text in the window using the Tesseract-OCR engine [51], and displays a digital version in Arial, size 30, with high contrast (black text on a white background) in a separate region below the window.

In accordance with DG4, we plan to incorporate an input method into ForeSee. In this study, as we only focused on understanding possible output formats on the head-mounted display, we used Wizard of Oz (WOZ) to allow users to interact with ForeSee with natural speech commands. Based on the study of different output effects, we will determine what kind of input actions ForeSee should support in the future to provide users more natural and flexible experience.

3.3 Prototype

We describe the current implementation of ForeSee. To create a video see-through system, we combined an Oculus Rift and a webcam. We used a WideCam F100 to capture the surrounding environment and an Oculus Rift DK2 with Lens B as the display on which we rendered both the captured environment as the background and different enhanced effects to enable users to get more visual information. The Oculus had a display with a resolution of 960x1080 for each eye. The webcam supported a resolution of 1920x1080 pixels with a 120 Degree ultra wide angle lens and allows manual focus. The webcam and Oculus Rift were connected to a laptop that is used as the processor of the vision enhancement system. The whole system was built with Unity and we used OpenCV to process video frames in real-time. The webcam was attached to the front of the Oculus Rift at the center between the user's eyes. The Oculus's two screens rendered the same images of the enhanced environment to simulate the effect of binocular vision.

Users interacted with ForeSee with natural speech commands, which we implemented with Wizard of Oz (WOZ). The researcher, acting as the wizard, responded to the commands and adjusted the system parameters accordingly. For example, the user could say, "move the window down," to adjust the window position in the Window Display Mode, or "make it larger," to adjust the magnification level in the Magnification Enhancement Method.

4. EVALUATION

We evaluated ForeSee by conducting a user study with 19 low vision participants. Our high-level goal was to determine whether ForeSee was a promising tool for people with low vision. Moreover, we sought to answer the following questions:

1. How did ForeSee affect people's visual experience in different scenarios?
2. How effective were each of the enhancement methods and display modes?
3. How did people customize ForeSee?

4.1 Method

4.1.1 Participants

We recruited 19 people with low vision to participate in our study (13 females, 6 males). Their mean age was 46 (age range: 21 – 68). In our recruiting materials, we called for volunteers who had "low vision" When volunteers contacted us, we conducted a brief interview over the phone to determine whether they were appropriate. If a volunteer said they used tools that enhanced their vision such as handheld magnifiers, screen magnifiers, or CCTVs, we deemed them appropriate. Participants had a variety of vision conditions (see Table 1). They all knew their diagnosed eye condition, but many did not know their precise visual acuity or visual field.

We had conducted studies with 20 participants, but one participant, P20, was unable to complete the tasks so we do not include this participant in our report. P20 arrived late and did not understand the study instructions.

Participants were compensated $20 per hour and were reimbursed for travel expenses up to $60.

4.1.2 Procedure and Materials

The study consisted of one session that lasted two to four hours (about 2.5 hours on average). Participants sat on a chair inside a well-lit office throughout the study. We offered them water and coffee and allowed them to take frequent breaks for as long as they needed to reduce the impact of exhaustion and possible fatigue on our study. We began each session by conducting a short interview where we asked participants for their age, gender, and vision condition. We then introduced ForeSee, explaining its functionality and the goals of the study.

We then asked participants to perform a set of tasks. In this paper, we focus on two of those tasks, which took about 1.5 hours on average. The tasks included reading text from (1) a handheld printed page and (2) four printed signs hung about three meters

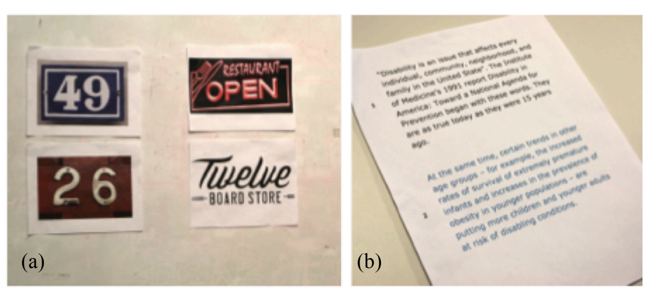

Figure 3. Experiment Materials: (a) four printed signs of numbers or writings hung on the wall (b) a handheld printed page

away. We chose these tasks because they were representative of important and challenging daily activities. The printed page had three paragraphs in Verdana, size 20, as shown in Figure 3(b). The letters were dark on the white page. The signs included several letters or numbers each, printed in a decorative font in different colors, as shown in Figure 3(a).

For each task, the participants were asked to think aloud about their visual experience under different conditions. Specifically, we asked them to describe what they saw, their comfort level (*i.e.*, whether they experienced any eyestrain), and read the text if possible. In total, we evaluated 12 conditions for each task:

1. Completing the task without using ForeSee.
2. Using ForeSee but without any enhancement methods.
3. Using ForeSee in the Full Display Mode, with all enhancement methods, except for Text Extraction, which can only be used in the Window Display Mode (conditions 3a – 3d).
4. Using ForeSee in the Window Display Mode, with each of the five enhancement methods (conditions 4a – 4e).
5. Using ForeSee with whatever enhancement methods (It is allowed to chose multiple enhancements at the same time and combine them.) and display mode works best. The user is able to take his or her time and customize the system to maximize their visual experience.

To avoid order effects, we counterbalanced the order of some conditions and randomized the order of others. We counterbalanced the order of the tasks (near-distance and far-distance) and the order of conditions 1 and 2. We presented the enhancement methods in a random order (condition 3a – 3d and 4a – 4e), since there were too many enhancement methods to properly counterbalance them. We always presented condition 5 at the end since participants had to be familiar with all the enhancement methods and both display modes to experience it effectively.

We connected ForeSee to the researcher's laptop, mirroring the display of the Oculus on the laptop. The researcher could thus ensure that the targets were in the user's field of view.

4.1.3 Analysis

We video-recorded and took notes during each session. After the study, we transcribed the videos using a professional service and analyzed the transcripts following the general method in [7], organizing them by tasks and conditions. Two researchers discussed the themes and categories of the data together, while one of them was mainly in charge of the coding process.

4.2 Results

In this section, we report user preferences and use patterns on different enhancement methods and display modes. Among our 19 participants, P5 and P15 did not have enough vision to benefit from ForeSee on either task, so they were not able to comment on the enhancement methods of display modes.

4.2.1 Video See-Through View (No Enhancements)

In Condition 2, participants completed a task by looking at the 2D video captured by the webcam. Considering the limited focal range of the webcam and the low resolutions of the Oculus display, we expected the unenhanced view to be blurry and distorted. However, some participants preferred the video see-through display to their original vision.

In the near-distance task, 9 participants indicated that using ForeSee without enhancement improved their visual experience. Some of them (*e.g.*, P12, P14) who could not read the materials with their original vision were able to read with ForeSee. "I can't read standard printed material without magnification. With the [ForeSee], I can see an individual word" (P14). Other participants (*e.g.*, P11, P16) said ForeSee increased the distance at which they could comfortably hold the page. "The difference is that I really have to look very close [without ForeSee], so if I had [ForeSee] I wouldn't have to look this close" (P16).

In the far-distance task, most participants preferred their original vision because of the limited resolution. However, there were still three participants (P2, P14, and P16) who believed that the visual experience with ForeSee was better.

4.2.2 Magnification

Full Display Mode: Most participants felt magnification was effective: 14 participants in the near-distance task and 15 in the far-distance task. Many remarked that magnification enabled them to see more colors and details. "I certainly see more detail than before. Now the color [of the top left sign] is green or blue, like a light green or blue" (P18). Even though the magnified video has a lower resolution than the original video, participants felt they perceived more information and were better able to distinguish details and read. "It's not so clear, but clear enough to maybe read it" (P4), and "But now that it's bigger, it's blurry but I can see more" (P2).

While providing more detailed information, magnification had some disadvantages. It reduced users' visual field and made it difficult for them to identify targets. It also reduced the speed at which they perceived what they saw, especially for the near-distance task:

So much of reading is recognizing general forms and not necessarily seeing every letter. Instead of actually looking at every single letter or every single syllable. I'm doing a lot from context. (P11)

The loss in visual field negatively impacted people with tunnel vision. Two participants (P3 and P9) insisted that magnification did not improve their vision in either task: "Everything that I look at cuts in half, so although they are becoming clearer, they're cut in half for me" (P3).

Window Display Mode: In the near-distance task, fewer participants liked magnification in the Window mode than in the Full mode. One reason is that the size of the window was limited, which reduced the users' field of view and also made it difficult to track the target. "Because I'm looking inside the box, it's fine, but I just stay focused inside the box. I don't like to go outside the box. It's too much. You could miss a sentence, you could skip over a line" (P10). While in the far-distance task, targets appeared smaller, which reduced the "cut-off" and "lose tracking" phenomena, which resulted in 13 participants finding magnification useful.

Participants tended to modify the size of the window as they adjusted the magnification level, increasing the window to keep the target in the magnified view. Some suggested that the window display should automatically increase as the magnification level increases to keep the target in the window. As P8 suggested, "Actually the magnification is helping but you need the border to magnify together with it. If you don't, then what you see inside the border decreases."

4.2.3 Contrast Enhancement

Full Display Mode: Like magnification, many participants (13 out of 19) felt that contrast enhancement was beneficial. They noted that the contrast enhancement emphasized the color and increased the sharpness: “It's brighter. It's sharper. That makes it easier to recognize what it is right away” (P16).

However, contrast enhancement also had a negative effect on some participants’ visual experience, especially those who were sensitive to light such as P2 and P10. They felt that the brightness hurt their eyes and distracted them from their ability to focus on the target. “It’s too bright. The color bothers me, I don't know how to explain it ” (P10).

Window Display Mode: Contrast enhancement was effective for more participants in the Window mode than in the Full mode. Participants no longer reported negative side effects. Moreover, we found that the window actually increased the effect of the contrast enhancement. P13 explained, “I realized something: when you add the borders [in the Window Display Mode], it increases the light in the area. The reading area seems brighter when you add the borders” (P13). The high contrast in the window, which was described as a flashlight by P12, highlighted the target and helped users locate and concentrate on the content they wanted to see: “It does highlight it. If you wanted me to focus on the ‘Z,’ it would help find it. It's easier to focus” (P12).

4.2.4 Edge Enhancement

Participants had strong and differing opinions about edge enhancement.

In the near-distance task, all participants except for P5 and P15 agreed that the font appeared bolder. For example, P10 explained, “It's bold. Let's say with low vision, you always have a problem with differentiating ‘e’ and ‘a’. It [edge enhancement] gives you a clear definition to the letter. It defines the letter.” However, six participants did not like this enhancement method in the near-distance task. Because the contours of each letter was thickened, it created a *crowding effect* [41] that made it difficult to read. “They're a little bit even bolder and a little bit closer together. It's a little bit harder to distinguish them” (P11).

In the far-distance task, most of the participants (14 out of 19), especially those who had more functional vision (*e.g*., P1, P12), felt edge enhancement was distracting because it added “unfamiliar” information to the objects. The edges darkened the scene and occluded colors and details in the original objects. As P13 commented, “I can't see the color distinction as clearly. It's blurrier and the images to me seemed thicker. They don't seem natural. They seem thicker.” Meanwhile, some participants (*e.g.*, P12 P17) did feel that edge enhancement helped to discover objects in their view and locate them quickly. “With the edge definition, the objects are more obviously there, because they're dark” (P12).

4.2.5 Black/White Reversal

As black/white reversal was modeled after a common effect people use when reading with CCTVs, it largely distorted the color and detail information of the objects in one’s environment. Unsurprisingly, most participants (15 out of 19) did not like this enhancement method in the far-distance task.

In the near-distance task, participants had differing opinions. Ten participants preferred the black/white reversal to the original black-on-white text. It was easier for them to perceive light against the dark background than to perceive dark letters on a light background. They said there was too much glare on the original white background, which they found distracting. As P13 mentioned, “I like [black/white reversal] because there's less glare from the paper, the page. I find it's easy to see every individual letter. I like that the words are enhanced better.”

On the other hand, there were seven participants who thought black-on-white was better than the reverse. They felt that the white letters were too bright, which hurt their eyes and caused fatigue. “It would be more tiring over a longer period of time because I would be getting too much glare from the letters” (P4).

4.2.6 Text Extraction

Participants had different opinions on text extraction due to different tasks. In the far-distance task, 11 participants felt that they benefited from the text extraction because it was much clearer than the original one. “I feel like if it was used for like a street sign, then that would be great. I really like the text detection. I pretty much can’t see the numbers without the text detection” (P2). While in the near-distance task, fewer participants (six out of 19) preferred text extraction. Seven participants concerned about the efficiency and practicability to extract only a few words at a time when reading long paragraphs. As P17 indicated, “It's great if you're looking at distance because usually a sign or something is not going to be more than a few words, but to read like that would take you a very long time. I don't think it's practical, maybe somehow superimposing it over.” Some of them (*e.g.*, P4, P11) suggested using eye-movement tracking and automatic text extraction to increase the reading efficiency.

We also discussed the presentation of the extracted text and the ability to control parameters in this task with participants to get insights about its design.

Participants wanted to be able to customize the position and style of the extracted text. Some participants felt the current location of the text (at the bottom of the display) was best because the text did not cover the center of their view (*e.g.*, P7, P10), and looking down felt natural for reading (P6). Seven participants (not counting P5 and P15), especially those with tunnel vision, had difficulty seeing the extracted text at the bottom of the display. The style of the digital text, including font size, color, and weight needed to be adjustable as well. P12 said the text extraction did not help because the text was too small for him to see. P18 suggested reversing the color of the text to white-on-black and using a bold font.

Switching their gaze between the original text in the window and the extracted digital text at the bottom of the display was challenging for some participants (*e.g.*, P6, P11). As P6 said, “I won't see the two images at the same time. I have to look at the image and then I have to look down. I have to change my position of my gaze.” Some participants (P6, P10) suggested that the extracted text could replace or be located next to the original text to avoid the gaze switching.

4.2.7 Window Display Mode

We summarize general user opinions and use patterns when using the Window Display Mode. Overall, six participants preferred using the Window in the near-distance task and 12 participants in the far-distance task.

Window placement: As we expected, most participants (13 out of 19) put the selection area at the location where their sight was best (usually in the center; for P3, it’s the left side because she only had vision on the left side of her right eye) and adjusted its size to fit the target object. However, P16 had a different approach. She also put the window in the center of her visual field and adjusted its size according to her target. However, she did this to compensate for a weak angle in her view. “I think to keep it center for me will always be good because that's, as I said, that's where my problem vision is, my central vision."

***Benefits**:* Participants reported several benefits from using the Window. Some (*e.g.*, P3, P18) said the window helped them concentrate on the target. Three participants (P7, P17, and P18) used the window to support multitasking. It was difficult for participants to switch from one task to another when using enhancements like magnification and black/white reversal in the Full Display Mode. For example, P17 felt disoriented when using black/white reversal: "Because, yeah, as long as you don't take your eyes off the page you're good. The second you look up, you're very disoriented." In the Window Display Mode, some participants felt the window enabled them to conduct different tasks at the same time. P7 explained:

I'm trying to think of a situation where I was reading something at my desk and if I wanted to be able to keep track of the things going on around me, then I would use the enhancement box set to a thin line so I could get the text.

Finally, some participants (*e.g.*, P1, P17) mentioned that the Window Display Mode gave people context (*i.e.*, information about the original image), especially in the far-distance task.

It gives me a point of comparison, because I can be not looking at it. I see now that I need help to zoom in, so now I see contextually. As opposed to when it's full blown, maybe the issue I had before was I don't know where I am in a world that large. I think just contextually this [can help me see]. (P17)

Weaknesses: There are also some weaknesses of the Window Display Mode mentioned by the participants. Participants with a better peripheral vision (*e.g.*, P1, P4, P17) felt the inconsistency between inside and outside of the window distracted them because they would see the surrounding of the window peripherally. For example, P17 commented on the magnification in Window Display Mode: "There are too many text sizes going on at once. Because I'm still seeing the text changing size as I'm reading it peripherally and it's a little distracting" (P17).

Some participants (*e.g.*, P2, P12) found it difficult to find the window in their visual field. "It was probably worse because then you have to find the specific spot" (P2). What's more, most participants prefer to set the window at a fixed position and then look around to move the target in. Some of them (*e.g.*, P16, P19) felt that it required too much effort to put the particular object into the small window, especially for the crowded text in the near-distance reading task, "It's hard to put the specific line into this area. It's frustrating" (P16).

4.2.8 Combining Enhancement Methods

Most participants (15 out of 19 in the near-distance task and 14 out of 19 in the far-distance task) felt that they were able to improve their visual experience by combining enhancement methods. Figure 4 shows which methods participants chose to achieve the best visual experience.

We found that participants' preferences differed in the two tasks. All the participants changed their preferred combination according to the viewing tasks. For example, more participants (10 out of 17 participants, not including P5 and P15) chose the Full Display Mode than the Window Mode in near-distance tasks.

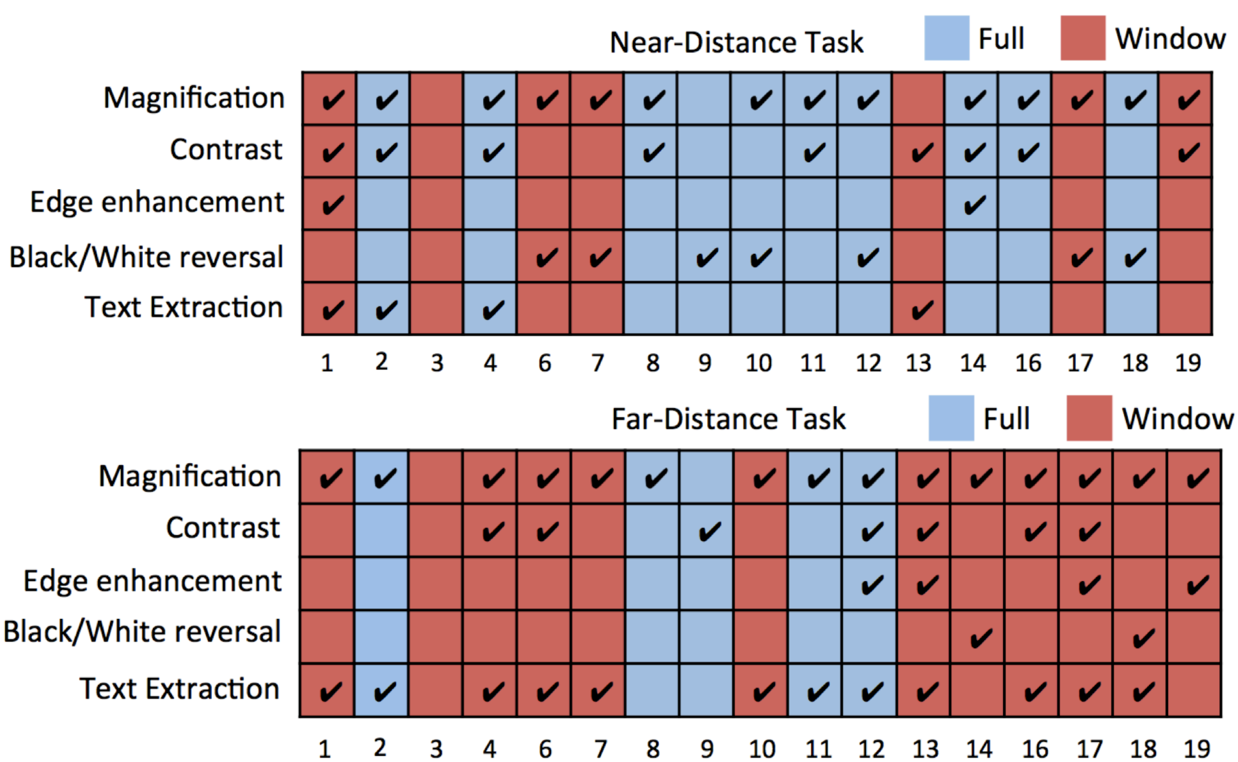

Figure 4. Enhancement method combinations preferred by each participant in the near- and far-distance tasks: The columns represent the participants (P5 and P15 are not shown because they could not conduct the combination), and the rows present the enhancement methods. We use red and blue to represent Full and Window Display Modes, respectively. In each row, we use a check mark "✔" to show the particular enhancements each participant chose in the combination. P3 has no check marks because she preferred the Window Display Mode without any enhancement in both tasks.

But most of them preferred the Window Display Mode in far-distance tasks (12 out of 17 participants) because the target is much smaller in this scenario and the window could help them focus. More participants preferred text extraction in the far-distance task (12 out of 17) than in the near-distance task (4 out of 17) because extracting all the words one by one in a large amount of text, such as the printed page that the participants used in the near-distance task, is time-consuming and not practicle.

Participants with different visual conditions chose different combinations in the same task. For example, participants with tunnel vision (*e.g.*, P3, P9) rarely chose magnification because they felt the objects were cut off too much. Participants who have more issues with colors, especially low-contrast colors (*e.g.*, P12, P17), were more likely to choose edge enhancement in the their preferred combination because it could enhance the contrast and emphasize the shape of the target.

Additionally, we found that most participants (14 out of 19 in the near-distance task and 15 out of 19 in the far-distance task) used magnification. Especially in the far-distance task, we found that other enhancement methods would only work with magnification. P12, for example, didn't feel that edge enhancement alone was beneficial in the far-distance task. However, when combing it with magnification, he said:

The edge enhancement probably helped. Plus you've got magnification going too, right? Now I could see the contour of the inside part. The edging really helped me distinguish the number.

5. DISCUSSION

Overall, we found that ForeSee was a promising vision enhancement tool for people with a wide range of vision abilities. In this section, we discuss the high-level findings, limitations, and challenges of the system and the study.

ForeSee was useful for a wide variety of visual conditions, but it would not be appropriate for people with too little functional vision (like P5 and P15), and people with too much vision. As we had expected, people who could not benefit from existing vision enhancement tools like CCTV's were also not able to benefit from ForeSee. We had designed our screening question accordingly, but we misunderstood P5's and P15's responses. During the study we found that they weren't able to perceive the difference among enhancement methods so ForeSee had no impact on their vision. On the other end of the spectrum, ForeSee is not appropriate for people with too much functional vision, such as P1, because either the 2D display or the reduced resolution would hinder their ability to see certain details. We believe that in the future, as video see-through technology advances, the resolution of the camera and the display will increase, and even fully sighted people will not perceive less information. ForeSee will then be able to enhance the vision of people with corrected and mildly low vision.

A key finding from the study was that customization (or "adaptability" [16,48]) was extremely useful. Participants improved their visual experience by combining enhancement methods and changing parameters of the enhancement methods and display modes. This was proved by our study, in which no participants chose the same combination for both tasks, shown in Figure 4. In fact, participants wanted even more ways to customize the system. When using Text Extraction, for example, they wanted to be able to modify the properties of the extracted digital text. Prior work on low vision has tended to focus on specific vision abilities [50,52] or tasks [15,20]. In contrast, we have shown how a single vision enhancement system can support a wide variety of vision abilities and tasks through rich customization. There was as much diversity of preferences among people with similar vision conditions as there was among people with different vision conditions.

The vast array of customization options can only improve the system if (1) users discover these options and (2) they can quickly adjust them. As we found in our study, people's preferences differed by task. In a real life setting, users would need to adjust the system quickly as they performed different daily activities. It is necessary to design suitable input methods to enable users to flexibly customize their visual effect on the go. Eyes-free input gestures and natural dialog systems are potential options that we are considering to help users optimize their experience or discover different settings. Additionally, we could use machine learning to learn the user's preferences and sense information in the environment (lighting condition, distance to target object, *etc.*) to automatically adjust the enhancement methods and display modes. This opens diverse and important opportunities for future work.

Another key finding from our study was that the Window Display Mode was effective for most participants, especially in the far-distance task. They explained that it helped them concentrate on the target, understand its context, and switch their gaze between tasks. However, some participants found it hard to use the window because of the inconsistency between inside and outside of the window and the difficulty to locate the window. Participants also raised an interesting direction for improving the window by automatically adjusting its size to the magnification level to keep their target in its view. Moreover, it would be interesting to adapt the *shape* of the window as well to match the target object. Exploring the properties of Window Display Mode is thus an important contribution of our work, which also differentiates our system from existing head-mounted displays (*e.g.*, eSight) and prior research.

Despite the overall positive results, the current ForeSee prototype and our study also had some limitations.

The social acceptability of the system is an important concern. Some participants (*e.g.*, P2, P11) complained about the bulkiness and intrusiveness of the current form factor. However, ForeSee is a preliminary prototype that we created to demonstrate the concept of a customizable head-mounted system and we did not expect that users would wear the current prototype in their daily life. We aimed to use this system as a first step to explore peoples' responses to different enhancement methods and modes, and get insights for future system designs.

There were also some limitations with the system implementation. As we mentioned, the resolutions of both the web camera and the Oculus display was relatively low. Moreover, processing the video feed also caused a slight delay. These factors negatively impacted the participants' attitudes towards ForeSee, but on the other hand, we gained a better understanding of the limitations of current hardware and software from the study with this prototype. This could direct researchers to develop smaller, lighter, and more suitable hardware, and more efficient algorithms for the future head-mounted system. We hope that a smaller head-mounted display with a higher resolution could be adopted to create a more acceptable system, allowing people to wear it everywhere as usual glasses. We may also use GPU computing in the future to speed up the system and provide more natural experience for the low vision users.

We faced several challenges when conducting the user study. Visual perception is complex and it was challenging to determine the effect of the different enhancement methods. During the study, participants sometimes had difficulty describing what they saw and how the enhancement methods affected their visual experience. We had to repeat and explain our questions several times and verify our understanding of the participants' description to ensure that we understood their experience. Although this process was difficult, we got interesting results as well as a deeper understanding about the benefits and weaknesses of different enhancements, which we would never get from a quantitative study.

6. CONCLUSION & FUTURE WORK

In this paper, we have presented ForeSee, a video see-through augmented reality system that improves the visual experience for people with low vision by directly enhancing what they see. ForeSee runs on commodity hardware. It captures a live video feed of the user's environment, applies some combination of enhancement methods (*e.g.*, magnification, contrast enhancement, and edge enhancement), and presents the modified video to users in real time. Through an extensive study with 19 low vision participants, we found that ForeSee's powerful customization abilities enabled people with different visual abilities to better see objects in different viewing tasks.

Our work has raised interesting directions for the future, including:

1. **Make ForeSee more practical.** We will explore ways of using lighter commodity software with higher resolution and more processing power (*e.g.*, a GPU) to reduce ForeSee's bulkiness and delay.
2. **Design efficient and natural interaction techniques**. We will explore a suitable input modality for users to customize ForeSee. Different modalities, such as speech commands, 3D gestures (*e.g.*, pointing, waving), eyes-free gestures on a smartwatch or wristband, eyes-free gestures on a smartphone or similar handheld device, or gestures on the head-mounted device itself (*e.g.*, the touchpad on Google Glass), will all be taken into consideration.
3. **Make ForeSee adaptive** [16]. Given the difficulties that low vision people may have in controlling the system, we will explore ways of using machine learning and sensors to learn the user's preferences in different environmental conditions. We will then develop algorithms to automatically adapt the enhancement methods and display modes to suit the user's needs in different contexts. We will also design suitable interactions to make sure the users could control the system manually when the system makes a mistake in the adaption.

As augmented and virtual reality technologies continue to advance, we believe ForeSee will become a powerful vision enhancement tool for people with low and even standard vision.

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