CueSee: Exploring Visual Cues for People with Low Vision to Facilitate a Visual Search Task

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ABSTRACT
Visual search is a major challenge for low vision people. Conventional vision enhancements like magnification help low vision people see more details, but cannot indicate the location of a target in a visual search task. In this paper, we explore visual cues—a new approach to facilitate visual search tasks for low vision people. We focus on product search and present *CueSee*, an augmented reality application on a head-mounted display (HMD) that facilitates product search by recognizing the product automatically and using visual cues to direct the user's attention to the product. We designed five visual cues that users can combine to suit their visual condition. We evaluated the visual cues with 12 low vision participants and found that participants preferred using our cues to conventional enhancements for product search. We also found that CueSee outperformed participants' best-corrected vision in both time and accuracy.

Author Keywords
Low vision; augmented reality; head-mounted systems.

ACM Classification Keywords
H.5.1. Information Interfaces and Presentations: Multimedia Information Systems; K.4.2. Computers and Society: Social Issues.

INTRODUCTION
Low vision is a pervasive disability. About 19 million people in the US have difficulty seeing even when using corrective contact lenses or glasses [8]. There are different kinds of low vision, including limited peripheral or central vision, blurry vision, light sensitivity, or blind spots [2]. All these conditions cause challenges in people's daily activities like traveling, socializing, and reading [10].

A variety of low vision aids including optical and digital magnifiers [43,49] and assistive software like screen magnifiers [30,46] and contrast enhancement [18,41] often help low vision people access information on digital devices and in the world around them [34,55]. These assistive technologies use vision enhancement methods that enable people to see more detailed (i.e., high frequency) information [37,54]. However, even when using magnification or other enhancements, low vision people cannot see and perform tasks as well as sighted people. For example, magnification enables low vision people to read print that they would not otherwise be able to read, but their reading speeds are still much slower than sighted people's reading speeds: while the average reading speed of a sighted person was 250 words per minute (WPM), one study found that with suitable magnification the reading speed of low vision people with intact central vision was 130 WPM, and the reading speed of people with limited central vision was only 25 WPM [28].

While vision enhancement technologies help low vision people see details, they are not designed to assist with other visual tasks. One common and challenging task is visual search, finding a particular known target from a selection of distractors. People perform visual search tasks during many daily activities. People search for a desired product in a store while shopping, look for a friend in a crowd while socializing, search for a key word in a document when working, *etc*. Consider the following use case. Sarah has low vision and she's looking for a box of Tylenol Extra Strength 500mg Caplets. She stands in a store medicine aisle and attempts to find the correct Tylenol product out of dozens of similar-looking products: Tylenol Cold and Flue, Tylenol Regular Strength, the generic versions of these products, *etc*. She could use her magnifying glass to examine a product individually, using it to read the print and determine whether it's the one she wants. This would be too slow because the magnifying glass helps her examine only one product at a time from a close distance; she has no way of efficiently scanning the shelves. Frustrated, she ends up asking a sighted person for help.

We propose a new approach to low vision accessibility: using computer vision to identify a target in a visual search task and presenting *visual cues* that attract and direct a low vision person's attention to the target, enabling her to conduct a visual search task more efficiently. We focus on the product search use case described above, which is both common and challenging. The dense arrays of products on grocery store shelves create a crowding effect [39] that

UbiComp '16, September 12-16, 2016, Heidelberg, Germany

DOI: http://dx.doi.org/10.1145/2971648.2971730

hinders low vision people's ability to see detail while co-located products tend to look similar to one another and often have low-contrast text [10]. We designed CueSee (Figure 1), an augmented reality application on a head-mounted display that facilitates a product search task by recognizing a target product automatically and using visual cues to direct a low vision person's attention to it.

Figure 1. (a) An illustration of a low vision person using CueSee to facilitate a visual search task in a grocery store with augmented reality (AR) glasses. (b) The user sees visual cues, specifically designed for low vision, which direct her attention to the product.

We explored designs for five visual cues that are central to CueSee: *Guideline*, *Spotlight*, *Flash*, *Movement*, and *Sunrays.* Since the human visual system is complex and there are many different kinds of low vision conditions, designing visual cues for low vision is challenging. A cue that a sighted person can easily see (*e.g.*, a red dot) may be outside a low vision user's field of view or may not have sufficient contrast with the background for a low vision user. We address this problem by designing cues that account for different low vision conditions [2,3] and cognitive psychology theories on attention [31,53]. We explored the effectiveness of the cues in the product search context and evaluated our application as a whole, demonstrating the potential of this new approach to low vision accessibility.

In summary, we contribute CueSee, an augmented reality application that enables low vision people to perform product search tasks more easily. CueSee demonstrates a new approach to low vision accessibility that improves access to many daily visual search tasks.

RELATED WORK

We discuss related work from three directions of research: approaches to low vision aids, visual cues to direct people's attention, and existing systems that facilitate product search for visually impaired people.

Approaches to Low Vision Aids

A variety of low vision tools were designed to help low vision people access more information.

The main approach to improve visual access to information is detail enhancement through magnification, contrast enhancement, and color reversal. Assistive technologies use these enhancement methods. For example, people could use optical low vision tools such as handheld magnifiers, reading glasses, monocular telescopes [49] for magnification. They can also use portable or stationary CCTVs [56], which magnify the video captured by a camera onto a digital display and allow users to increase the contrast or invert colors in the display. There are also some screen magnifiers (e.g., [4,16]) built-in on mainstream platforms and standalone software applications (e.g., Magic [30] and ZoomText [46]) used to enlarge web pages and font sizes to help low vision people access digital information. These tools often allow people to change the contrast or invert the color of the display.

Researchers developed some new assistive technologies [5,17,25] using these enhancement methods. For example, Bigham [5] presented an approach to improve website accessibility by magnifying elements in a webpage in an optimal way, without causing negative side effects like scrolling and element overlap. Researchers also implemented and evaluated enhancement methods on head-mounted displays. For example, ForeSee [54] was a head-mounted vision enhancement system which supported five different vision enhancement methods (e.g., magnification) and two display modes, allowing low vision users to customize their visual experience according to their eye conditions and usage scenarios. Hwang and Peli [21] developed an edge enhancement Google Glass application that increases contrast for people with age-related macular degeneration. These enhancement methods helped low vision people read and recognize faces, but did not address the challenges of visual search tasks [42].

Another approach to help people with a limited field of view is increasing their visual field. Peripheral prism glasses [27] are a low vision optical device with high power prism segments embedded in regular glasses, which expand people's vision by optically shifting objects from outside the user's visual field to a functional area in the field. Researchers have explored an approach to visual field expansion on head-mounted displays called vision multiplexing, where the contours of a wide field are minified and presented over the user's functional field of view [36,38,48]. Luo and Peli [29] studied the impact of vision multiplexing on visual search and found that vision multiplexing improved people's visual search performance in a larger search area, but its impact on a smaller search area depended on people's visual field and gaze speed. Although this method helped people see objects out of their field of view in a visual search task, it does not highlight a known target during visual search and the contour of a wider area provides limited visual information about potential targets.

Visual Cues to Direct People's Attention

In the HCI field, researchers have designed different visual cues to direct users' attention and help them find targets. Kline and Glinert [23] presented ColorEyes, a visual indicator in the form of cartoon eyes that were designed to help low vision people find the mouse cursor in a GUI. Sukan *et al.* [12] directed users' heads and eyes to a particular orientation and target by defining a virtual frustum to constrain the positions they could look at and the angles they could look from. Hong *et al*. [20] conducted a user study with 186 sighted people to explore the effect of a flash animation on attracting users' attention to a product on a shopping website. They found that the flash animation did attract users' attention and helped them find a target.

Cognitive psychology researchers examined visual cues like target onset and movement to determine whether they attract people's attention more effectively. For example, McLeod *et al*. [31] conducted a study to examine whether moving items can capture people's attention. They asked participants to conduct a visual search task in two conditions: a moving target among half moving and half stationary items, and a static target among all stationary items. They found that participants spent less time finding the moving target in half moving and half stationary items. Yantis and Jonides [52] conducted a study to explore the effect of abrupt onset on attracting people's attention to targets. Eighteen participants conducted a standard visual search task, determining whether a target letter was on a display. Their performance (accuracy and reaction time) improved when the target letters appeared with an abrupt onset compared to when the targets appeared gradually. The results show that the visual system is sensitive to onset stimuli and this property attracts attention.

Although different visual cues were designed and explored in both HCI and cognitive psychology literature, most cues were designed for and evaluated with sighted people. It is unclear whether visual cues can help low vision people and how such cues should be designed.

Facilitating Product Search for Visually Impaired People

Product search is a major challenge for low vision [10] and blind people, but, to our knowledge, all prior work in this area has focused on interaction with audio and tactile output designed for people with no functional vision.

Some prior research facilitated product search by using computer vision techniques to locate products and provided audio feedback to guide users to the target. Bigham *et al*. [6] presented VizWiz::LocateIt to enable blind people to find a target product on a shelf with their smartphone. The user took a photo of the general shelf and sent it to a human-powered service that could manually select the target product in the photo. The system then recognized the product using SURF or color histograms and output a clicking sound or speech to guide the user to the product. Foo also used computer vision techniques to facilitate product search by presenting GroZi [13], a handheld grocery shopping assistant that located products with OCR and product-recognition algorithms and guided blind people to a target with 3D audio effects with a Wiimote.

Some researchers used barcode and RFID scanning technologies to enable blind users to identify products on a shelf [14,26]. For example, Trinetra [26] is a mobile application, with which visually impaired people scanned RFID tags on products and received product information in the form of speech through a Bluetooth headset. While these systems enabled blind people to locate a product on a shelf, users could not perform an efficient search by scanning all products one by one. Nicholson *et al*. [35] aimed to increase product search efficiency by designing ShopTalk, a wearable system with a barcode scanner, which updated a user's location based on the barcode she was scanning and directed her to the target product with verbal directions. Kulyukin *et al*. upgraded ShopTalk to ShopMobile [24] by developing a vision-based barcode scanning method on a smartphone. The main drawback to ShopTalk and ShopMobile was that they required a large amount of pre-stored information, such as a topological map of the locomotor space and the product information (e.g., product location) associated with each barcode.

MOTIVATING STUDY

Previous work has showed that shopping is challenging for low vision people [10]. However, it is still unknown that what strategies and tools low vision people are using to conduct product search. We conducted a pre-exploration study with 11 low vision participants (six males and five females) to understand the challenges low vision people encountered in product search [47]. We tasked them with finding a certain Tylenol product in a local pharmacy and used contextual inquiry [19] to observe and interview them during the task. We found that locating a product on a shelf was challenging for low vision people, especially seeing details on the product box (*e.g.*, brands and flavors). Most participants stood several inches away from the shelf and laboriously picked up each product and closely examined it to find the correct Tylenol box. Also, most participants did not use assistive devices during the product search process, but instead, they often asked other people for help. We found that there were few technologies that helped participants in the store, which highlighted a gap in assistive technology for visual search tasks. This work motivated us to create an assistive tool that would help low vision people search for products on a grocery store shelf independently and efficiently.

THE DESIGN OF CUESEE

Design Guidelines

We formulated the following guidelines to direct the design of CueSee:

DG1. Provide Direct Visual Feedback

We aim to design an augmented reality application with direct visual feedback to leverage low vision people's residual functional vision for a visual search task [45]. With the emerging head-mounted display platforms, we can use computer vision and image processing technologies to develop new types of visual feedback for low vision people that beyond the capability of standard glasses.

DG2. Minimize Invasiveness

We need to minimize the invasiveness of the visual feedback. Since people may want to see and verify the target product and explore other products with their own vision, visual feedback should not obstruct users' view of their surroundings or prevent them from seeing information on the target product.

DG3. Design for Different Visual Abilities

We aim to create a method that would fit people with a wide range of visual abilities. There are many different kinds and degrees of vision impairments [2] and people's visual abilities often change over time and in different environments [33]. We will design different visual cues allowing users to select from and combine to suit more users' needs and preferences.

DG4. Support Hands-Free Interaction

We seek to enable a hands-free interaction for low vision people when they are searching for products on a shelf. People typically take a basket or a cart with them when shopping in the store. Some low vision people may also hold a cane, which would make it difficult for them to control an extra device (*e.g.*, a barcode scanner [26]). It is important to design an interaction that frees people's hands and enables a convenient search experience.

Design of Visual Cues

We designed five visual cues for low vision based on different visual conditions [2,3] and cognitive psychology theories [31,53].

Guideline. The location of the target is indicated with a red guideline connecting the center of the display and the center of the target (Figure 2c). If low vision users have reduced peripheral vision, they could find the target by following the guideline with their central vision.

Spotlight. We simulate the effect of a spotlight by changing the image into gray scale while leaving the target in its original colors (Figure 2d). This visual cue makes the target stand out by increasing the color differences between the target and all the other products, which could benefit people with low contrast sensitivity.

Flash. Onset was shown to be an effective method to attract people's attention [53]. For low vision people, we use flash, which displays a set of onsets continuously to increase the impact of the onset stimuli. We create a flash effect by adding a rectangular frame around the target and alternating its color between black and gray every 0.5 second (Figure 2e (1)-(2)). We used a frame because it would not cover the front of the target.

Movement. Movement is another effective feature to attract people's attention [31]. We generate this effect by rotating the product. With the center of the target as an anchor, we rotate the product between -30, 0, and 30 degree every 0.5 second (Figure 2f(1)-(2)). We chose rotation because it would not change the general location of the product.

Sunrays. We add eight red guidelines that converge at the center of the target. The lines start from the border of the target and end at the border of the video feed (Figure 2g). These guidelines are visible even to people who have blind spots or very limited fields of view.

Description of CueSee

CueSee is an augmented reality application that facilitates visual search by guiding users' attention to a pre-specified target. We design CueSee on a video see-through HMD that has already been adopted by researchers and companies as a platform to create low vision technologies [11,54]. We chose this platform because it could act as an always-available display that renders direct visual feedback (DG1) and users could wear it all the time without holding with their hands (DG4). Meanwhile, as HMDs become more pervasive and socially acceptable [51], low vision people will likely begin to use them as accessibility tools [40,44]. CueSee processes an HMD's camera feed, and renders an enhanced video on the display. We focused on users' visual search experience, assuming they could pre-select a product using an existing input method.

CueSee is designed to leverage the state-of-the-art computer vision algorithms and frameworks to train models of products in grocery store and localize them in real-time. There has been much research on object recognition [1,22]

Figure 2. The Visual Cues in CueSee: a) the original picture of a target product on the shelf; b) the basic enhancement on the target with magnification and higher contrast, c) Guideline; d) Spotlight; e) Flash, the color of the frame changes between grey (e1) and black (e2); f) Movement, the target rotates between -30 (f1) and 30 (f2) degrees; g) Sunrays; and h) a combination of Spotlight and Sunrays.

and also some research specifically on product recognition [32,50]. When running on a HMD, CueSee can use these algorithms to recognize a pre-specified product without requiring in-store instrumentation like prior work [15,35].

The interaction flow of CueSee was inspired by the way a sighted person searches for a product on a shelf: she simply glances at the shelf, quickly identifies the product if it's in her field of view, and reaches for it. With CueSee, a low vision person glances at the shelf, allowing the computer vision algorithms to identify the target product in real time if it's in the camera's field of view. CueSee then renders visual cues to direct the user's attention to the target so she can reach for it quickly. CueSee provides five visual cues and users could select and combine the cues they preferred according to their visual abilities (DG3). In accordance with DG2, we render the visual cues around the target to prevent it from covering the product information. In addition to the cues, CueSee enhances the target product with 1.5x magnification and a contrast enhancement (Figure 2b) to enable the user to see the detailed product information [54]. When the users get close to the target, the visual cues disappear leaving the enhancement on the target to minimize visual clutter and obstructions, following DG2.

CueSee focused on searching for pre-specified targets. In real-life scenarios, a user could input the target products into CueSee as a shopping list before she arrives at a grocery store, which could increase the efficiency of the product search. We will design interaction techniques for CueSee to specify target products in our future work.

EVALUATION

We conducted a user study with 12 low vision participants. Our high-level goal was to examine the effectiveness of the visual cues in attracting people's attention and assessing CueSee's effectiveness in facilitating a product search task.

Method

Participants

We recruited 12 low vision people (six males, six females) for our study. Their mea age was 44 (range=23-68). We conducted a screening phone interview to determine whether the volunteers fit for our study. If a volunteer indicated that she used assistive tools that enhanced her vision like magnifiers or CCTVs, we regarded her as a good fit. Volunteers who only used screen readers were not considered suitable. Participants had a variety of vision conditions (Table 1). They were compensated $20 per hour and were reimbursed for travel expenses up to $60.

Apparatus

We built a prototype video see-through HMD system (Figure 3b) and used it to evaluate CueSee and the effect of all visual cues. The HMD prototype consisted of an Oculus Rift DK2 and a Logitech C920 webcam. We used the webcam to capture the surrounding and rendered the captured environment on the Oculus display to simulate users' original vision. The Oculus and webcam were connected to a laptop that recognized products and generated the visual cues. The webcam was attached to the front of the Oculus Rift at the center between the users' eyes. We rendered the same images of the environment with visual cues on the Oculus' two displays to simulate the effect of binocular vision.

To minimize the confounding effect of computer vision accuracy, we used a relatively accurate marker recognition technique to identify products. We attached Chilitag

ID	Age/ Sex	Diagnosis	Legally Blind	Visual Acuity	Visual Field	Color Vision	Tools Used
P1	59/F	Retinitis Pigmentosa	Yes	20/50 with magnification	Less than 5 degree	Have issues with subtle colors	Bold, large text with reversed colors on the computer; smart phone applications (KNFB and EyeNote)
P2	55/F	Steven-Johnson Syndrome	Yes	Left: 20/150 right: 20/200	Very limited peripheral vision	Good color vision	Magnifier, QuickLook device, CCTV, don't have smartphone
P3	59/F	Retinopathy of Prematurity	Yes	Left: 20/400 right: 20/300	Full visual field	Need high contrast	Handhld monocular, CCTV, handheld magnifier, ZoomText (magnification & speech)
P4	23/M	Stargardt's Disease	No	Limited, but unknown	Full visual field	More issues with contrast	Assessible software on Mac (Zoom), color reversal
P5	37/M	Reversal Class of Retinitis Pigmentosa	Yes	20/300	Full, central vision is depressed	Issues with low contrast colors	Magnification, speech, color reveral
P6	32/M	Prematurity of Retinas; Nystagmus	Yes	20/200	Full	Good color vision	Applications on the phone - VoiceOver, Grabber (text extraction) & AmpliVision (magnification)
P7	54/M	Stargardt's Disease	Yes	Left: 20/800 right: 20/600	Full	Have some color deficiencies	Portable, digital magnifier; CCTV; hand-held telescopes; optical telescopes
P8	23/M	Nystagmus; No pigment inside of eye	No	20/120	Full	Good color vision	Bifocal, telescope, software magnifier, zoom-in function on computer
P9	34/F	Retinitis Pigmentosa; Cataract	Yes	Left: 20/80 right: 20/60	Tunnel vision	Have issues with subtle colors	Magnifier, spotlight at night
P10	60/F	Wet Form Macular Degeneration	Yes	Unknown, left is much worse than right	Full	Cannot see colors through certain area in the central vision	Prescription glasses; magnifying glasses; magnification app (over 40 Magnifier and Flashlight) and dictation on iphone
P11	27/M	Retinobiastoma	Yes	Left: 20/140 with correction right: blind	Only have bottom part of the central vision	Need high contrast; cannot see subtle colors	Screen reader; magnifier and color reversal on computer; magnifier and camera on phone (SuperVision+ Magnifier; KNFB reader)
P12	68/F	Retinopathy; Cataract	Yes	Left: 20/80 right: blind	Limited in left eye	Issues with low contrast colors	Zoomtext, CCTV, color reverse, handheld magnifiers, iPhone w/Zoom + Siri

Table 1. Demographic information of the 12 participants

markers [9] to each product and identified the products identity and location based on its marker.

When the processer recognized the marker corresponding to the target product, it enhanced the exact rectangular area that the product was located by adding a 1.5x magnification and a higher color contrast (setting the RGB values of each pixel with a multiplication of 2 and an addition of -100). The system also rendered the user's preferred visual cues on the Oculus displays according to the product's location. We calculated the distance between the target product and the camera based on the size of the marker. When the distance was smaller than one foot, the visual cues disappeared leaving the enhancement.

The whole system was built with C# and we used OpenCV to generate different visual cues. The frame rate of the prototype system was around 20 fps. Since we focused on users' visual search experience, we did not implement input methods to CueSee. A researcher controlled CueSee for participants by selecting their preferred visual cues and specifying target products in the user study. We mirrored the HMD display on a laptop screen to monitor what the participants could see with CueSee in the user study.

We set up a mock grocery store shelf by putting 24 unique products on a four-layer bookshelf (78" Height x 48" Width x 24" Depth) with six products on each row (Figure 3a). Some products were made by the same brands but had different flavors.

Figure 3. (a) A mock grocery store shelf with 24 products; (b) the video see-through HMD prototype; (c) a participant standing one meter away from the shelf conducting a product search task with CueSee.

Procedure

The user study consisted of one session that lasted 1.5 to 2 hours. We allowed participants to take frequent breaks. We began the study with a pre-evaluation where we asked participants about their demographic information and shopping experience.

We first evaluated the effectiveness of the different visual cues qualitatively. The participants wore the prototype and stood one meter away from the mock shelf (Figure 3c). We demonstrated the basic enhancement (Figure 2b) first and then all five visual cues, directing them to the same target product (Figure 2c-2g) one by one in a random order. We asked participants to think aloud about their visual experience in each condition. Specifically, we asked them to describe whether they noticed the visual cue easily, how effective was the cue, what was their comfort level (i.e., whether they experienced any eyestrain), why they liked or disliked the cue, and what modifications could improve the cue. After trying all visual cues, participants selected their favorite cue, which could be made up of one or more of the original five cues. If they combined cues, we asked them to try the combination to verify its effectiveness. They could also select the basic enhancement with no visual cue. The selected cue was then used throughout the experiment to evaluate CueSee.

Next, we evaluated CueSee as a whole by asking participants to conduct a product search task in front of the mock grocery store shelf. Participants stood one meter away from the shelf and performed the product search task in two conditions: (1) with CueSee using their preferred visual cue, and (2) with best correction (using their own standard glasses or contact lenses). They performed five practice tasks followed by ten recorded tasks for each condition. We counterbalanced the order among the 12 participants. Between each set of five trails, we randomized the location of each product on the shelf to minimize the effect of memorization but kept the products from the same brands together to simulate a real grocery store shelf layout.

For all search tasks, we instructed participants to search for a target product as quickly as possible. A participant began a task by standing one meter away from the shelf and closing her eyes so she would not get a head start on the search. We then randomly selected a product and told the participant the product brand, name, and flavor. We asked the participant to repeat the information to ensure she heard it correctly. Then we said, "Start," and the participant opened her eyes and began to search for the product. She needed to touch the target product and say "Found it!" to confirm that she completed the task. We recorded the search time as the time between "Start" and "Found it". If the participant confirmed a wrong product as the target or gave up on the task, we regarded it as wrong.

Lastly, we compared participants' performance with CueSee to their performance with an assistive device, if they typically used one when searching for products. Participants conducted the same product search task described above with their own assistive devices. We conducted a post-evaluation after the experiment, asking participants to assess the effectiveness and comfort level of their preferred visual cue with scores ranging from 1 to 7 (completely unsatisfied to completely satisfied).

Analysis and Design

We video-recorded the interviews, transcribed the video recordings using a professional service, and coded participants' responses to different visual cues following the general method in [7]. Two researchers discussed the themes and categories of the data together, while one of them was mainly in charge of the coding process.

We analyzed whether CueSee outperformed best correction in terms of time and accuracy. Our experiment had one within-subject factor, *Condition* (*CueSee*, *BestCorrection*) and two measures: *Time* and *Accuracy*. We defined a *Trial* (1-10) as one search task. We computed the Time by having two researchers independently record the search time in the ten trials for each condition and calculating the mean time between the two researchers. The correlation between the two researchers was 0.999. We recorded the Accuracy by observing whether the participants touched the correct product in each trial.

We generated boxplots to confirm that Time was roughly normally distributed and analyzed the difference in participants' mean search times across conditions with a paired t-test. Accuracy was not normally distributed, so we used a Wilcoxon Signed Rank test to compare the accuracy between the two conditions.

To validate counterbalancing, we added another between-subject factor, *Order* (two levels: *BestCorrection-CueSee* and *CueSee-BestCorrection*), into our model. Since Time was normally distributed, we modeled it with a linear mixed-effects model with *Participant* as a random effect and found no significant effect of Order on search time ($F_{(1,10)}$=1.11, p=0.32) and no significant effect of interaction between Order and Condition on search time ($F_{(1,10)}$=0.23, p=0.64). Accuracy was not normally distributed, so we used a Kruskal-Wallis test to evaluate the effect of Order and did not find a significant effect of Order on Accuracy as well ($H_{(1)}$=0.02, p=0.89). These results indicated adequate counterbalancing and no asymmetric skill transfer.

Results

Effectiveness of Visual Cues

We report our qualitative findings that capture participants' responses and behavior when using the different cues.

Basic Enhancement. None of the participants preferred to use the basic enhancement without any visual cues. They felt that, even though the magnification and higher contrast could help them see more details after they located and neared the target, the enhancement was not conspicuous enough to attract their attention when they were not focusing on the particular product. Four participants (*e.g.*, P1, P2) did not notice the basic enhancement from one meter away. Some participants wanted to remove the basic enhancement because it changed the size of the product and made it harder to grasp. As P11 mentioned, "I think it's better to leave the item itself in normal vision, then it would be easier to go and reach for it and grab it."

Guideline. Five participants said Guideline was an effective visual cue. These participants had better vision than the others. They could clearly see the guideline and follow it to get the location of the product. As P4 indicated, "It definitely stands out. As long as [the target is] in my field of view, [the guideline] seems to point to it." Some participants also felt Guideline was less distracting than the other cues. "I would probably stick with this one if I was in a grocery store because with this one nothing changes dramatically except the line shows you where it is" (P6).

The other seven participants who had more severe low vision had difficulty seeing Guideline. This was mostly because the line was not thick enough and its color did not contrast enough with the surroundings. Some tunnel vision participants did not prefer Guideline because it was not directional. For example, P9 had tunnel vision but a good visual acuity. When the visual cue appeared, she saw the red line clearly but only part of it—the starting point from the center was missing (it seemed that her focus was not at the exact center). She described her experience: "The line is okay, but you don't know which way to go, look up or down." This implicated that every part of the guideline should be directional for the convenience of people with tunnel vision. P9 also suggested improving Guideline by changing the thickness of the line gradually from the center to the target product, which would indicate its direction immediately from any part of the line.

Participants had differing opinions about Guideline's color. Six participants thought red could attract their attention, while the other half could not distinguish it very well. Participants all expressed interest in customizing the color by themselves. Some participants (*e.g.*, P2 and P10) also mentioned that they would like CueSee to take the color of the target into consideration and make the color of Guideline adaptive. As P10 suggested, "A lot of packages have red on it, so it's easier to confuse red with the package. [The color of Guideline] should depend on what color I was looking for."

Spotlight. Seven participants agreed that Spotlight could attract their attention because it brought higher contrast with the background and helped them focus on the target. As P1 mentioned, "I know the object is there because it is more lit up as compared to the objects that don't have these colors." Some participants (e.g., P6, P9) also thought it minimized the distraction when compared with other visual cues. "There's zero distraction. People with peripheral vision loss don't want a lot going on" (P9).

However, for the other five participants who had more difficulty perceiving color, this visual cue was difficult to notice. For example, P11 indicated, "In this light, I can't totally tell that difference. That's only for people who have good color perception." Another feedback on Spotlight was that it was not directional, which made it hard for the users to locate the product. As P4 mentioned, "If I'm looking at one corner, everything suddenly [turns into] gray, then I still have to look around. Oh, where is the color?" He suggested that this visual cue was better to use with some directional visual cues such as Guideline and Sunrays. P1 was also concerned about losing contextual information about the products around the target. As she described, "Sometimes I want to see whether there are new flavors next to it, so it's greyed out and now I can't tell what the other things are."

Flash. Five participants who had ultra low vision found Flash extremely helpful for them. The flashing effect attracted their attention, and the rectangular shape framed the product and helped them focus on it. As P2 commented, "It really framed [the target product]. It's eye catching and I can definitely see it."

The other seven participants found Flash too distracting. "It's distracting as far as what I'm trying to focus on, especially if I'm trying to read something there" (P6). Some participants (*e.g.*, P3, P7) also felt tired after using this visual cue. As P3 mentioned, "I think it's just more tiring on the eyes, so I could see it would be strenuous after a while." Some participants (*e.g.*, P7, P10) suggested slowing down the flashing to make it less distracting.

Movement. None of the participants liked Movement because it was distracting and prevented them from reading the product's information. It was hard for the participants to read text on tilting or moving objects. Even though movement attracted their attention well, they didn't like not being able to confirm the product's identity. P1 explained: "It definitely gets your attention but I don't like it. I couldn't read to confirm it. I'm using my eyes, I want to see what I'm looking at." Some participants (*e.g.*, P8, P12) suggested rotating the product more slowly and to a smaller degree. P8 also suggested pausing the movement when the user looked directly at it.

Sunrays. Six participants believed Sunrays would be helpful. They felt this visual cue stood out and could effectively direct them to the product. "I like Sunrays because it just draws your eye there. It helps me focus in on what I'm doing" (P8). Participants who had limited central vision but better peripheral vision also benefited from this visual cue because Sunrays covered the whole screen, enabling people to see it with their peripheral vision. As P7 said, "It's more going from the peripheral to the center. My peripheral is better than my center, [so that I could see the visual cue well]."

However, the other six participants did not like this visual cue. Three of them felt it was overwhelming and obscured other products. "It's a little bit overkill. If I wanted to take a look at the products around, I can't even do that because the lines are in my way" (P6). Another three participants had difficulty with seeing this visual cue. They agreed that the design of Sunrays was helpful, but the red color was high contrast enough. They suggested using a brighter red, or flash the lines. Sunrays seemed more suitable for people with moderate low vision.

Visual Cue Preferences

Participants with different vision abilities preferred different visual cues (Figure 4). Five participants chose a single cue and the other seven combined different visual cues. Participants with mild low vision (*e.g.*, P4 and P8 who are not legally blind) preferred Guideline or Spotlight, while participants who have ultra low vision (*e.g.*, P1 and P11) usually chose Flash. However, no participants chose Movement as their favorite cue. We discuss possible reasons in *Effectiveness of Visual Cues*. Moreover, none of the participants chose the enhancement without any cues, indicating that the visual cues helped them localize the product more effectively than the basic enhancement.

Most participants indicated that their preferred visual cues were effective with a high comfort level. The mean effectiveness score was 6.33 (*SD*=1.0) and the mean comfort level score was 6.33 (*SD*=0.78). Eleven out of 12 participants gave a score of more than five for cue effectiveness. One participant (P9) gave a score of four, saying that her cue was not effective enough. Ten participants gave a score of more than six to the comfort level. The other two felt the visual cues were a little tiring after long-term use and gave a score of five.

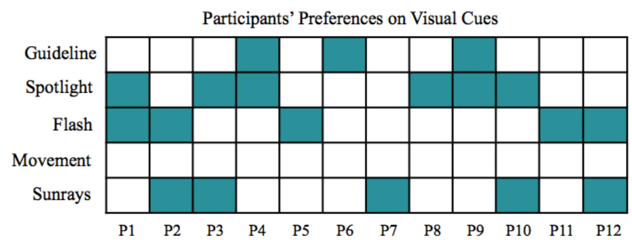

Figure 4. Visual cues preferred by each participant: we use filled in blocks to represent the visual cues (row) that each participant (column) chose to use in our study.

P9 was the only participant who thought the visual cues were not effective. After a brief discussion, we understood that (1) she had relatively high visual acuity (20/40 in her better eye) that enabled her to find a target product by herself relatively quickly; (2) she didn't trust CueSee and tried to find the products on her own, even when using CueSee; and (3) she had a very limited field of view (more than any other participant) and it was hard for her to locate all the cues. Although she could locate one of the lines in the Sunrays cue easily, it was hard for her to determine the direction to follow to find the target.

Effectiveness of CueSee

Search Time. We found that participants spent much less time with CueSee (*mean*=14.88s, *SD*=10.06s) than with their best correction (*mean*=27.73s, *SD*=24.66s) in the product search task (Figure 5). This result corresponds to a decrease of 46.34% of the search time for CueSee compared to BestCorrection. Figure 6 shows the mean search times for each participant in both conditions. Using a paired t-test, we found that there was a significant effect of Condition on Time (t_{11}=2.9068, p=0.014).

As shown in Figure 6, eleven out of 12 participants performed better with CueSee than with their best correction. P9, however, spent more time with CueSee (*mean*=12.567s) than with BestCorrection (*mean*=11.261), although this difference was not significant using a non-paired t-test ($t_{16.46}$=-0.45301, p=0.657). We discussed the reason in *Visual Cue Preferences* section.

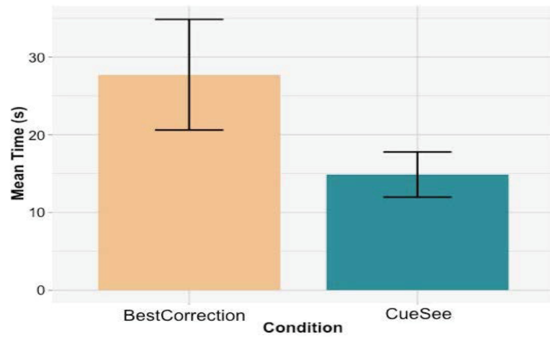

Figure 5. Mean search time for all participants when using BestCorrection and when using CueSee

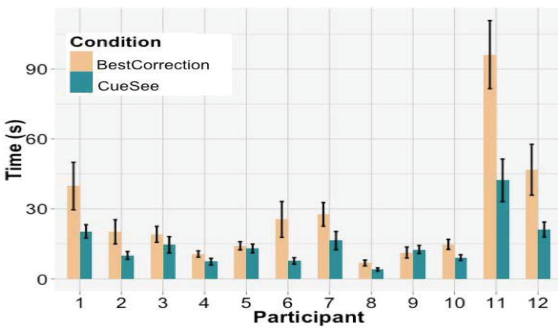

Figure 6. Mean search times for each participant with best correction (BestCorrection) and with CueSee.

Moreover, there was a significantly larger variance across participants when using BestCorection compared with CueSee using an F-test ($F_{(11,11)}$=0.17, p=0.01). This indicates that CueSee's performance was more consistent, despite participants' different visual conditions and abilities of locating target products.

Search Accuracy. Participants achieved 100 percent accuracy when using CueSee (*mean*=100%, *SD*=0). When using BestCorretion, their accuracy was slightly worse (*mean*=93.33%, *SD*=10.73%). Four participants occasionally picked the wrong products when using their best corrections (accuracy of P1: 80%, P2: 90%, P11: 70%, P12: 80%), while with CueSee their accuracy increased to 100%. Since our data set was small with many ties, we only got an estimated p-value (p=0.098) with a Wilcoxon Signed Rank test.

Assistive Technologies

Surprisingly, only two participants (P1, P11) typically used assistive technologies to help with product search during grocery shopping. P1 used a pair of binocular glasses, while P11 used the SuperVision+ iPhone application with 10% magnification and an embedded flashlight.

P1 and P11 performed the product search task with their assistive technologies (*AsstTech*). Although their own technologies also increased their search accuracy to 100%, the search time was much longer than using CueSee. As seen in Figure 7, CueSee outperformed BestCorrection as well as AsstTech in terms of time. The mean search time of P1 was reduced 25.47% when using CueSee (*mean*=20.37s) instead of her own assistive tool (*mean*=27.33s), and P11's search time was reduced 44.34% (CueSee: *mean*=42.27s, AsstTech: *mean*=75.94s).

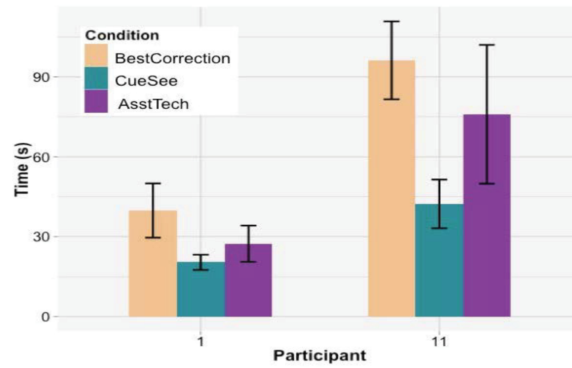

Figure 7. Mean search times for P1 and P11 when with BestCorrection, CueSee, and their own tools.

We observed how P1 and P11 used their assistive tools. Although these tools helped them see the products' information better, they still needed to get very close to the shelf and pick up each item to figure out whether it was the target product. This was especially true for P11, who used a magnification app and the flashlight on his iPhone. When he tried to find a product, he took out his phone, turned on the flashlight, and adjusted the magnification level. This took him longer than using CueSee.

DISCUSSION

Our study confirmed that using computer vision and visual cues enabled people to perform a visual search task more efficiently than with their best corrected vision. Only two participants used assistive tools for such a task and in the study, CueSee outperformed participants' assistive tools. Moreover, enhancement methods like magnification did not adequately support participants in completing the product search task. While participants had different preferences for visual cues, they all preferred using at least one cue to using the basic enhancement on its own. Even when the enhancement was applied only to the target product, it was still difficult for them to locate the product because the enhancing effect did not *attract* their attention.

People with different visual conditions had different preferences for visual cues. People with mild visual impairment (*e.g.*, P4 and P8) chose Guideline or Spotlight, while people with ultra low vision (P5 and P11) chose Flash. Sunrays benefited people with blind spots or tunnel vision (*e.g.,* P7 and P10). Participants did not like Movement because it prevented them from reading the information on the product. One improvement could be adding moving elements around the border instead of rotating the whole object. Besides different cue preferences, participants wanted to modify the cues and adjust their color, thickness, and shape. This highlighted the importance of customization in low vision technologies [54] and the need to make CueSee more customizable.

CueSee as a whole performed well in terms of speed and accuracy in the product search task. Interestingly, it also reduced the impact of different vision abilities and target characteristics like location and appearance on users' performance, making the search time more consistent.

CueSee changed participants' behavior during the product search task. With CueSee, participants located a product when standing one meter away from the shelf. Instead of getting close to the shelf and picking up each product to read the text on the box, they glanced at the shelf and reached for the product directly. Moreover, the products above or below eye level also became easier for then to find. Without CueSee, participants squatted or knelt (*e.g.*, P6, P7) to examine products on the lower shelves closely, but with CueSee they just leaned slightly to capture the products in the camera's field of view. While participants moved their head to capture all products on the shelves with CueSee's camera, they occasionally moved too quickly, preventing CueSee's computer vision algorithm from recognizing the product. In these cases, participants had to rescan the shelves, resulting in longer search times.

The CueSee prototype has some limitations. To avoid confounds from computer vision errors, our current prototype used markers on each product to identify and locate the target. Using markers produced more reliable computer vision recognition results. However, in a real-life scenario, there would be large amounts of products in a store and it would be impractical to put identifiers on each product. We would use computer vision techniques that enable CueSee to recognize different products in real-time without markers [32,50]. Of course, CueSee's effectiveness would hinge upon the effectiveness of those algorithms.

When using CueSee, some participants lost their spatial intuition and had difficulty grasping a product quickly and precisely. This is because we only had one camera and attached it to the front of the Oculus, bringing it closer to the products than the users' eyes. The Oculus was also big and heavy, making it impractical for real use because of physical discomfort and possible social stigma. This HMD platform was just a prototype to demonstrate the concept of CueSee, following a "technology push" approach. We plan to develop a lighter prototype in the future by using a stereo-camera with a much smaller HMD platform such as a Google cardboard. We are also designing cues for optical see-through glasses (Figure 1), since they project light over the user's natural vision and allow users to see the real world with their natural vision, which mitigates disorientation experienced in video see-through HMDs. However, these glasses are more limited in the kinds of visual processing techniques that can be performed (*e.g.*, magnification) and have more restricted fields of view.

The general approach of using visual cues also has limitations. It is designed for search tasks where the user knows (and specifies) the target and computer vision algorithms are able to locate the target. The approach does not aim to *replace* conventional enhancements, but to be used in conjunction with enhancements for certain tasks, as we demonstrated with CueSee.

CONCLUSION AND FUTURE WORK

In this paper, we presented CueSee, an augmented reality method that enables low vision people to find a product on a grocery store shelf independently and efficiently. Our study with 12 low vision participants showed that visual cues were an effective approach in directing low vision people's attention and people with different visual abilities have different preferences for visual cues. The study also showed CueSee was promising: it significantly reduced product search time and increased search accuracy to 100%.

Our work has raised interesting directions for the future. First, we will design suitable interaction techniques for CueSee users to input target products. Second, based on participants' feedback on different visual cues, we will improve CueSee by generating optimal visual cues for different users according to their visual conditions. We will also use eye-trackers to detect gaze direction and adjust the visual cues (*e.g.*, position) adaptively. Finally, we also plan to conduct the evaluation in more realistic scenarios, such as a real grocery store, to explore the feasibility of CueSee.

ACKNOWLEGEMENT

We thank Michele Hu, Catherine Feng, and all participants for their time and helpful feedback.

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