Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review

JUSTIN KASOWSKI, University of California, Santa Barbara, USA
BYRON A. JOHNSON, University of California, Santa Barbara, USA
RYAN NEYDAVOOD, University of California, Santa Barbara, USA
ANVITHA AKKARAJU, University of California, Santa Barbara, USA
MICHAEL BEYELER, University of California, Santa Barbara, USA

Over the past decade, extended reality (XR) applications have increasingly been used as assistive technology for people with low vision (LV). Here we present a systematic literature review of 216 publications from 109 different venues assessing the potential of XR technology to serve as not just a visual accessibility aid but also as a tool to study perception and behavior in people with low vision and blind people whose vision was restored with a visual neuroprosthesis. These technologies may be used to visually enhance a person’s environment for completing daily activities, train LV participants with residual vision, or simulate either a specific visual impairment or the artificial vision generated by a prosthetic implant. We also highlight the need for adequate empirical evaluation, the broadening of end-user participation, and a more nuanced understanding of the suitability and usability of different XR-based accessibility aids.

CCS Concepts:
- Human-centered computing → Accessibility; Mixed / augmented reality; Virtual reality; Visualization systems and tools.

Additional Key Words and Phrases: Systematic Literature Review, Assistive Technology, Virtual Reality, Augmented Reality, Blind, Low Vision

ACM Reference Format:
Justin Kasowski, Byron A. Johnson, Ryan Neydavood, Anvitha Akkaraju, and Michael Beyeler. 2021. Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review. 1, 1 (September 2021), 20 pages. https://doi.org/10.1145/nnnnnn.nnnnnnn

1 INTRODUCTION

In recent years, rapid technological advances have led to an increase in the number of assistive technology and electronic mobility aids for people who are blind or have low vision (BLV) [12, 14, 44, 70]. These assistive devices use various sensors (e.g., cameras, depth and ultrasonic sensors) to capture the environment and often apply computer vision and signal processing techniques to detect, recognize, or enhance text, people, and obstacles. Some systems translate vision into alternative modalities, such as converting a visual object into auditory or haptic signals [70]. Although vision substitution techniques would be essential for people who are completely blind, the majority of people with low vision...
(LV) have useful residual vision and prefer to use it to observe the environment [44]. Some head-mounted display (HMD) systems such as Google Glass [33, 46, 84], Microsoft HoloLens [45, 53, 90], and Oculus Rift [79] allow the user to make head and body movements that are typically too noisy for psychophysics experiments. These state-of-the-art devices facilitate the development and implementation of complex computer vision algorithms that may improve orientation and mobility in people with LV [40, 95, 114].

To make the best use of these emerging technologies as LV aids, it is valuable to understand what types of vision enhancements and information processing have already been identified as helpful in improving visual function and thus quality of life for their end users. It is also valuable to take into account important human factor considerations, such as the individual preferences and accessibility needs of people with different levels of residual vision and underlying conditions, which are likely to determine the success and usability of extended reality (XR)-based visual aids.

XR includes virtual reality (VR), augmented reality (AR), and other immersive environments that have not yet been invented. While there is some overlap, experiments with VR technology allow researchers to monitor participants in a controlled 3D environment while AR devices integrate and enhance real surroundings. Subject performance has been evaluated with cognitive tasks, physical tasks, or some combination of the two extensively in XR [9, 37, 61, 74, 106]. Moreover, XR technology is increasingly being used to study visual perception in blind people whose vision was restored with a visual neuroprosthesis [28].

The goal of this review is thus to summarize studies that evaluate XR devices designed for improving quality of life for people who are blind or have low vision, and identify trends that can inform the development of future assistive technologies. In serve of this, we make three contributions:

1. We provide a systematic literature review of 216 publications from 109 different venues assessing the potential of XR technology development to further visual accessibility. In contrast to other reviews, we sample studies from multiple scientific disciplines, require studies to feature a quantitative evaluation with appropriate end users, and focus on accessibility aids that visually augment a person’s residual vision.
2. We perform a meta-analysis that gives a holistic view of the prevalent types of XR technologies used in LV research and shows how the landscape has changed over the last ten years.
3. We identify scientific gaps and highlight the need for real-world validation, the broadening of end-user participation, and a more nuanced understanding of the suitability and usability of different XR-based accessibility aids.

2 MOTIVATION
2.1 Why XR for Low Vision?
XR technologies offer new ways of interacting with digital media. However, such technologies are not well explored for people with different ranges of abilities beyond a few specific navigation and gaming applications. While new standardization activities are investigating accessibility issues with existing AR/VR systems, commercial systems are still confined to specialized hardware and software limiting their widespread adoption among people with disabilities. Smart glasses and VR headsets were originally invented to improve productivity and provide entertainment but are now being studied as assistive devices for BLV.

Our definition of XR includes handheld magnifiers, smartphones, CCTVs, and HMD systems, because they all provide a visual enhancement, either handheld or worn, to the user that would otherwise not exist. These devices are designed for reading, object recognition, website accessibility/usability, and orientation/mobility. While XR can
be used to improved quality of life in BLV, it can also be used to simulate low vision conditions for sighted people. Experiments with BLV are often resource intensive given the clinical guidelines needed to collect data from people in this group. Simulated low vision (SLV) allows researchers to study behavior associated with the conditions seen in BLV with sighted participants. This also includes simulated prosthetic vision (SPV), in which sighted people view their environment under conditions similar to what people with prosthetic implants would see. We therefore also wanted to show what has been going on this space, and how this emerging area relates to the more established areas of accessibility research. Activity in this multidisciplinary is not just confined to human-computer interaction, but also includes research in psychology, vision research, and clinical research.

Given the rapid rate at which new research is being conducted in the use of these new assistive technologies, it is timely to review the field in order to better understand the nature of this research.

2.2 The Value of Systematic Reviews

Systematic reviews are undertaken to examine a research field more holistically by understanding its recent area of focus, the gaps, and looking to the future of the field. In contrast to a traditional review, systematic reviews can provide a more complete and less biased picture of the type of work being undertaken in the field and point to key challenges moving forward [78]. They not only identify the current state of the art, but also the gaps that are yet to be addressed and provide data for rational decision making.

There is evidence of the benefit of systematic reviews within the domain of assistive technologies. Kelly and Smith [52] performed systematically examined the research literature on assistive technology from and found that most studies lacked methodological rigor. More recently, Brule et al. [12] highlighted the need for adequate quantitative empirical evaluation by involving BLV end users in the design process. This sentiment was shared by Butler et al. [14], who further highlighted the need to broaden application areas and asked for more in situ evaluation.

These works demonstrate that systematic reviews can highlight key issues in accessibility research and provoke the field to reflect and improve on their practice.

3 METHODS

3.1 Scope

The purpose of this work was to identify the progress made over the last decade, identifying gaps in current practices, and making a number of specific recommendations for future research in this area. Specifically, the goal was to answer a number of questions regarding the use of XR in LV research:

- What are the main types of XR technologies used in LV research?
- What experimental tasks are studied?
- What are key challenges or scientific gaps that researchers should focus on in the future?

XR is a universal term that encompasses VR, AR, and mixed reality. To define “reality”, we required studies allowing users to interact with an immersive environment. Being able to move one’s body has been identified as a key factor for immersion [82], and studies were excluded if they did not update the environment based on the participant’s eye or head movements. Studies with monitors usually do not allow for head or body movements, but can still be used to represent a virtual space if complemented with head/eye tracking. Smart devices (and their applications) were only included if they were used to augment the environment (as opposed to, for example, a website) in some way. For example, a text magnifier that could be pointed at text in real life would be included, but an on-screen text magnifying app would not.
A large number of visual accessibility devices may operate on visual information as input modality (e.g., by locating nearby obstacles), but then offer nonvisual feedback to the user (e.g., via text-to-speech software or vibrotactile devices). These devices include electronic travel aids, electronic orientation aids, position locator devices, and sensory substitution devices. Although such devices can form the basis of practical accessibility aids, some of which have proved very effective in the past, they have also been reviewed extensively (for a recent review, see [70]). We therefore wanted to focus our review on accessibility aids that offer visual feedback to the user (e.g., by visually augmenting the scene in an AR display) with the goal of enhancing their residual vision.

We also required all studies to feature human subjects research and behavioral metrics. While much has been written about the theoretical and technical aspects of accessibility technology, we specifically wanted to focus on studies that incorporated appropriate quantitative empirical evaluation, as suggested by [12]. Articles were excluded if not an original work (e.g., review papers), solely proposed new technology or methods, or were focused on a survey about basic device use (i.e., “how often do you use your smart device to read text”). Survey studies were included if they focused on participants’ perceived experience while using a specific technology.

3.2 Systematic Review Process

To perform a systematic review for the use of XR in BLV research, we followed the PRISMA protocol [80] as outlined in Fig. 1. PRISMA is a method for systematically searching databases with a list of keywords and documenting at every step the number of papers excluded from further analysis along with the reasons for exclusion. This procedure is designed to help reduce bias and encourage a holistic review.

To cover a large body of research independent of their publication venue, we searched three databases (Google Scholar, IEEE Xplore, and PubMed) on Dec 5, 2020 with different keyword pairs (Table 1) designed to identify work that combined XR technology with low vision and accessibility research. Each database was searched with the most inclusive search parameters that did not result in a full-text search; that is, we searched the title alone with Google Scholar, title/abstract in PubMed, and title/abstract/author in IEEE Xplore. This resulted in exactly 10,000 matches across the three databases. We later manually added two prominent uses of AR for prosthetic vision [50, 75] that the keyword search had missed.

Table 1. Search terms used on Google Scholar, IEEE Xplore, and PubMed. Every term in the left column was combined with every term in the right column. “*” denotes the wildcard character.

| Visual impairment                  | Extended reality |
|-----------------------------------|------------------|
| “bionic vision”                   | “AR”             |
| “low*vision”                      | “augment*”       |
| “prosthetic vision”               | “device*”        |
| “retinal implant”                 | “display*”       |
| “retinal prosthesis”              | “enhance*”       |
| “vis* aid*”                       | “head-mounted”   |
| “vis* loss”                       | “immersive”      |
| “vis* impair*”                    | “mixed”          |
|                                  | “reality”        |
|                                  | “simulat*”       |
|                                  | “technolog*”     |
|                                  | “VR”             |
|                                  | “wearable”       |
Even though we deemed the pairwise combination of categorical keywords necessary to identify a wide variety of paper titles, this also resulted in a lot of duplicates. All identified articles were imported into Zotero, which identified 5,671 duplicates and 51 other articles whose publication date did not seem the match the criteria. The remaining 4,281 articles were reviewed by the research team and assessed for eligibility.

The majority of the remaining papers (n = 3,031) described various visual accessibility prototypes that operated on vision as an input modality (e.g., through optical character recognition or computer vision), but offered only nonvisual feedback to the user. Although a perfectly fine approach to accessibility aids for low vision, we deemed these papers as out of scope for the current review. In addition, we also had to remove a large number of studies that were purely theoretical or technical in nature, without evaluating their proposed design on end users (n = 862). Furthermore, we removed a number of papers that turned out to be duplicates missed by Zotero (n = 75), were not available in English (n = 65), or could not be located online (n = 33; most often manually entered citations on Google Scholar).

The remaining 216 studies (available as a BIB file in the Supplementary Materials) were included in the review.
4 META-ANALYSIS

4.1 Publications by Venue

Upon completion of the systematic review, we identified 216 papers from 109 different venues. 59 of these were conference publications (Table 2) that included full papers, workshop papers, and extended abstracts/short papers. The majority of papers were classified as full papers by their respective venue. Of the 34 different conference venues in our dataset, the most popular conference was the Annual Meeting of the IEEE Engineering in Medicine and Biology Society (EMBC) closely followed by ACM ASSETS and CHI. Not surprisingly, the range of conference venues also included top-tier conferences in mixed reality (e.g., IEEE VR, ISMAR, and UIST), accessible technology (ICCHP), and ubiquitous computing (e.g., UbiComp, PerCom, ACIIW). There were also a number that were considered short papers or extended abstracts that accompanied a poster presentation or demo. A small fraction of papers were part of a workshop or satellite event instead of the main conference track.

| Venue                | Full | Short | Workshop | Total |
|----------------------|------|-------|----------|-------|
| IEEE EMBC            | 11   | 0     | 0        | 11    |
| ACM ASSETS           | 3    | 5     | 0        | 8     |
| ACM CHI              | 5    | 1     | 0        | 6     |
| ICCHP                | 2    | 0     | 0        | 2     |
| IEEE VR              | 0    | 0     | 2        | 2     |
| CVPR                 | 0    | 0     | 2        | 2     |
| All others           | 19   | 6     | 3        | 28    |
| **Total**            | **40**| **12**| **7**    | **59**|

Table 2. Number of conference publications by venue.

The other 157 publications were full-length articles that appeared in one of 75 different scientific journals (Table 3). Here, the largest body of work appeared in vision science journals that specialize in either basic (e.g., Journal of Vision, Vision Research) or clinical research (e.g., Optometry & Vision Science, Investigative Ophthalmology & Visual Science, Translational Vision Science & Technology). A number of papers also appeared in biomedical engineering journals (e.g., Journal of Neural Engineering, IEEE Transactions) and general-purpose journals (e.g., PLOS ONE, Scientific Reports).

| Venue                                      | Count |
|--------------------------------------------|-------|
| Optometry & Vision Science                 | 12    |
| Journal of Vision                          | 10    |
| Journal of Neural Engineering              | 10    |
| Vision Research                            | 10    |
| PLOS ONE                                   | 8     |
| Ophthalmic & Physiological Optics (OPO)    | 8     |
| Artificial Organs                          | 7     |
| Investigative Ophthalmology & Visual Science (IOVS) | 6    |
| Translational Vision Science & Technology (TVST) | 4    |
| All others                                 | 82    |
| **Total**                                  | **157**|

Table 3. Number of journal articles by venue.
4.2 Publications by Authors

The 216 articles identified by our review process were written by 743 different authors. The gender distribution of these authors is shown in Table 4, separated by primary author (sometimes also called “first author”), supporting authors (“middle authors”) and senior authors (“last author”). Three papers were written by a single author; we counted them as primary authors. The gender of each author was inferred based on their first name using Gender API (https://gender-api.com), which is considered one of the most accurate gender inference services [87] as it is built upon various data sources that includes publicly available governmental records combined with data crawled from social networks.

| Gender   | Primary | Supporting | Senior | Total |
|----------|---------|------------|--------|-------|
| female   | (37 %)  | 80         | 213    | 346   |
| male     | (61 %)  | 132        | 474    | 758   |
| unknown  | (2 %)   | 4          | 14     | 23    |
| Total    | 216     | 701        | 210    | 1127  |

Table 4. Gender distribution of primary, middle, and senior authors.

Approximately 67 % of all authors were estimated to be male, 31 % were estimate to be female, and the remaining 2 % could not be categorized accordingly (Table 4). This gender disparity was preserved across primary, supporting, and senior authors. In addition, it is worth noting that women were much less likely to appear as senior authors as they were to appear as primary authors. Unfortunately, these trends are consistent with other studies that have documented the gender disparity in computer science and engineering [105].

4.3 Publications by Research Area

To get a better understanding of the research areas covered by the corpus of identified papers, we used the free online platform https://litmaps.co to create an interactive literature map. Here, each paper is represented by a circle whose size is proportional to the number of citations the paper received, and papers are clustered by title similarity (i.e., the closer two papers are on the graph, the more similar are their titles). A few select studies with a relatively large number of citations are highlighted as well. Upon inspection of the full literature map, three prominent (though not mutually exclusive) research areas became evident:

- **Visual Accessibility Technology** (green): studies that primarily focused on the development of novel assistive technologies, devices, and augmentation strategies. Per our eligibility criteria, all included studies involved human subjects research; most often by evaluating the appropriateness and effectiveness of a proposed design with members of the BLV community.

- **Low Vision XR** (red): studies that primarily used XR technology as a means to study visual perception and behavior under various visual impairments. Often these studies involved lenses, prisms, and goggles that would allow researchers to simulate a specific eye condition. Other studies used VR to study eye movements or to train members of the BLV community on a virtual version of a visually guided task.

- **Prosthetic Vision XR** (blue): studies that primarily used XR technology to simulate the artificial vision generated by a visual prosthesis. Often these studies tried to understand the perceptual consequences of a specific retinal implant design. Other studies used XR to evaluate the effectiveness of specific visual augmentation strategies.
We next wondered how the popularity of these three research areas changed over the last decade (Fig. 5). We found that the overall number of papers in the corpus has been steadily increasing over the years (note that all but the last column represent a two-year period). This rise was mostly due to increasing interest in the development of XR-based visual accessibility technology, followed by a rise in interest in Low Vision XR. Interest in Prosthetic Vision XR has been steady for most of the decade, with a brief period of increased activity in 2014–15, and what looks to be a potential comeback starting in 2020.

| Year  | 2010-11 | 2012-13 | 2014-15 | 2016-17 | 2018-19 | 2020 | Total |
|-------|---------|---------|---------|---------|---------|-------|-------|
| Visual Accessibility Technology | 4       | 6       | 5       | 16      | 24      | 15    | 70    |
| Low Vision XR | 13      | 13      | 14      | 14      | 18      | 19    | 91    |
| Prosthetic Vision XR | 9       | 8       | 14      | 9       | 9       | 6     | 55    |
| **Total** | **26**  | **27**  | **33**  | **39**  | **51**  | **40** | **216** |

Table 5. Number of publications per year and application area.

Interestingly, the recent rise in popularity of XR technologies can be attributed to AR wearables (Table 6), despite an increase in availability of handheld devices such as smart phones and tablets. Whereas VR devices were used throughout the 2010s, and the first half of the decade was dominated by the use of monitors and nonelectronic wearables (e.g., prisms, goggles, lenses), AR devices have become increasingly popular in recent years.

| Year  | 2010-11 | 2012-13 | 2014-15 | 2016-17 | 2018-2019 | 2020 | Total |
|-------|---------|---------|---------|---------|-----------|------|-------|
| Monitors | 4       | 10      | 9       | 8       | 8         | 5    | 44    |
| Nonelectronic wearables | 10      | 3       | 5       | 6       | 9         | 9    | 42    |
| Handheld devices | 0       | 1       | 1       | 6       | 5         | 1    | 14    |
| VR wearables | 13      | 11      | 12      | 8       | 13        | 13   | 70    |
| AR wearables | 0       | 2       | 6       | 10      | 17        | 11   | 46    |
| **Total** | **27**  | **27**  | **33**  | **38**  | **52**    | **39** | **216** |

Table 6. Number of publications per year and device type.

5 RESEARCH AREAS

5.1 Visual Accessibility Technology

XR technology offers great potential in prototyping systems for assistive technology. Here we focus on technologies that visually augment the environment; this can include any device, product, item, or software program that is used to enhance the visual sense of a BLV end user.

![Fig. 2. Overview of Visual Accessibility Technology studies (n = 70). Studies were categorized based on XR technology used (monitor-based; handheld devices such as magnifying glasses, smartphones, and tablets; VR-based; AR-based) and experimental tasks studied (low-level visual function testing; letter, word, and object recognition; spatial cognition, orientation, and mobility).](image-url)

Manuscript submitted to ACM
Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review

The distribution of visual accessibility technologies that employ XR is shown in Fig. 2. These include a range of XR devices (monitors: \( n = 3 \); handheld devices: \( n = 14 \); VR wearables: \( n = 17 \); AR wearables: \( n = 36 \)) evaluated on various experimental tasks (low-level visual function testing: \( n = 30 \); object recognition, reading, and visual search: \( n = 14 \); spatial cognition, orientation, and mobility: \( n = 26 \)).

In the following subsections, we will briefly summarize the findings of recent Visual Accessibility Technology studies and highlight some common limitations.

5.1.1 Device Types. XR-based visual accessibility technology can be split into systems relying on either wearable (\( n = 53 \)) or nonwearable devices (\( n = 17 \)). By far the most popular nonwearable device are smartphones and tablets, which have been used as electronic magnifiers [93, 109], reading aids [27, 76], and object recognition [71]. One interesting use case is a study by Mascetti and colleagues [71] that evaluated the use of a smartphone app to aid in the detection and visibility of traffic lights. Another study [15] used the user’s gaze as a pointing tool for smart magnification techniques and showed that this improved face identification for individuals with central vision loss.

With the advent of wearable XR technology, research now includes modern designs of HMD systems using AR, VR or some combination of the two [3, 11, 62, 96]. Popular AR devices in our corpus of papers include the Microsoft HoloLens (e.g., [53, 91]), Epson-Moverio BT-200 (e.g., [4, 117]), and the now discontinued Google Glass (e.g. [33, 84]). Popular VR devices were the Oculus Rift (e.g., [79]), HTC VIVE (e.g., [38, 88]) and Samsung’s Gear VR (e.g., [112]). These devices have been found to reduce stress related to movement in people with low vision [20]. As HMDs and smart glasses become available at reduced cost and in more compact form factors, their use in laboratory experiments and potential as a low vision aid is only expected to increase.

5.1.2 Visual Augmentation Strategies. Researchers have used wearable systems to study the use of image enhancement techniques for people with low vision [116, 120]. Given that a user with low vision has residual vision, image processing techniques can be used to enhance the surrounding environment and further assist in various daily tasks. SeeingVR is a set of fourteen visual enhancement tools that is designed to . When asked to navigate a menu, search for an object, or shoot a moving target with a HTC VIVE, eleven participants with low vision completed the tasks faster and more accurately with SeeingVR compared to without it [116]. These results are similar to other work with BLV using HMD systems to improve acuity wearing the Samsung Gear [35, 112], the eSight[110], and Google Glass [84]. This is also well aligned with findings using handheld devices (i.e. magnifiers, smart phones, and tablets), suggesting that HMD systems are comparable to low tech solutions for improving acuity and reading [39, 76, 109]. Hicks and colleagues (2013) tested a depth-based HMD prototype converting object distance into brightness values. Visual signals were converted via an LCD display attached to ski goggles. All eighteen participants were able to detect and react to visual objects when using the prototype. People with more severe levels of impairment (such as advanced RP) appeared to take longer when detecting objects [40].

Improvements with smart glasses in people with low vision have also been reported. Lang et. Al (2020) used the HoloLens to evaluate words and numbers compared to symbols in three people with low vision. Their device interpreted time on a watch and emotional expressions of faces by displaying simplified symbols via the HoloLens. When testing three people with visual impairment, participants preferred the AR enhancements over the real stimulus [57]. A separate study using the HoloLens to navigate an obstacle course found that the device would helpful in reducing collisions by 50 percent for people with RP [2]. Azenkot and Zhao (2017) used the Epson-Moverio BT-200 as a model for “CueSee”, and found that subjects identified items on a grocery shelf significantly faster using “CueSee” than their natural vision [4]. When asked to read text and signs using “ForeSee”, people with low vision preferred to combine multiple enhancement
methods for both near- and far-distance tasks [120]. Through the various studies highlighted, it has been illustrated that smart glasses and AR can be used to make significant improvements in people with vision loss.

5.1.3 Common Limitations. Although there is no shortage of publications that demonstrate a proof-of-concept that XR technology can be used as a low vision aid, few studies discuss the human-computer interaction (HCI) aspects of their proposed technology. For instance, Williams et al. compared sighted and blind navigation and found that both groups understand navigation differently, leading sighted people to struggle in guiding blind companions [52]. In addition, guide dog and white cane users navigate differently, thus suggesting that navigation technologies need to account for both travelling styles [53]. Many prototype studies might thus benefit from incorporating end users across all stages of the design process rather than as a final step for validation. In the future, studies should move away from observational, within-subject study designs and strive to evaluate new technologies using the randomized-control-trial study design with sufficient power (sample size) [44].

5.2 Low Vision in XR

XR technology is increasingly being used to study visual perception and behavior in people with low vision. Most of these studies either tried to predict visual outcomes by having sighted participants adapt to simulated low vision (SLV) designed to mimic certain visual impairments, or they used XR as a tool to study visual perception and behavior in people with low vision.

| XR Technology: | Monitors | Nonelectronic wearables | VR | AR |
|----------------|---------|------------------------|----|----|
| Experimental Task: | Acuity | Recognition | Spatial cognition |
| Level of Immersion: | not gaze-contingent | gaze-contingent |
| Visual Enhancement: | no | yes |

Fig. 3. Overview of Low Vision XR studies (n = 91). Studies were categorized based on XR technology used (monitor-based; nonelectronic wearables such as prisms, goggles, and lenses; VR-based; AR-based), experimental tasks studied (low-level visual function testing; letter, word, and object recognition; spatial cognition, orientation, and mobility), level of immersion considered (with or without compensating for eye movements), and intervention method (using simulations to impair vision, or also offering means to enhance the visual experience).

The distribution of low vision studies that employ XR is shown in Fig. 3. These include publications that study behavioral performance of people with low vision in various experimental tasks (low-level visual function testing: n = 11; object recognition, reading, and visual search: n = 49; spatial cognition, orientation, and mobility: n = 31), offering varying levels of immersion (viewing stimuli on a screen: n = 33; viewing stimuli through prisms, lenses, or goggles: n = 41; viewing stimuli through a VR HMD: n = 13; viewing stimuli through AR glasses: n = 4).

In the following subsections, we will briefly summarize the findings of recent low vision studies and highlight some common limitations.

5.2.1 Simulating Visual Impairment. Simulations are a valuable experimental tool for studying performance in tasks such as visual search [1, 47, 83], face perception [63, 99], reading [45, 58], and navigation [7, 32, 121]. While a blindfold

Manuscript submitted to ACM
Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review

is the easiest way to simulate impairment for a sighted participant, it is limited due to the instant removal of all visual information. In contrast, a large body of research uses nonelectronic wearables, such as specially designed lenses, filters, foils, glasses, and goggles as a cheap means to apply an impairment to sighted participants. Modern alternatives include the use of a gaze-contingent VR HMD, through which participants view stimuli that have been altered in real time using image processing to simulate a specific visual condition. This SLV-based viewing mode has been termed “altered reality” [5]. The primary advantage of this approach is the ability to flexibly remove, add, or modify many different features of visual input.

Visual impairment diseases such as age-related macular degeneration (AMD), glaucoma, and retinitis pigmentosa (RP) produce scotomas (i.e., concentric area(s) in the retina that do not function normally due to the disease [10, 34]), which lead to visual field loss (VFL). The consequences of VFL on eye-movement behavior have been studied extensively in the literature, typically by training sighted participants on a simulated scotoma with the help of a gaze-contingent display. For instance, people with central VFL shift their oculomotor reference location from the fovea to an eccentric area known as the preferred retinal locus (PRL) [10], and some studies have been able to reproduce this effect with SLV [1, 63], but not others [21, 55]. However, eye-movement behavior can vary drastically across tasks and impairment condition [55, 99], sometimes leading to notably different findings when comparing results from nonelectronic wearables to those that use a gaze-contingent HMD. Moreover, findings from research with central scotomas may not translate to peripheral scotomas [21], with some studies noting a difference between unilateral and bilateral VFL [19]. In another study, McIlreavy et al. [73] were able to show that search times for targets and spatial distribution of gaze increased as the size of the simulated scotoma increased. However, saccade amplitude and fixation duration remained unaffected. Overall these experiments have led to mixed results as to whether or not SLV is comparable to what people with low vision actually see.

A limited number of SLV studies tested the effectiveness of image enhancement techniques to support visual search and navigation tasks. For example, highlighting stair edges was more likely to prevent fall risk when the tread highlighter was placed 30 mm away from the physical edge instead of directly on top of it [31]. Other studies have shown that edge enhancement can improve contrast sensitivity [46] and help older participants in a visual search task [56]. However, none of these prototype systems were evaluated with BLV end users.

5.2.2 Studying Visual Perception and Behavior. Although the majority of papers have focused mainly on testing sighted participants with SLV, we identified a handful of studies whose goal was to use VR technology as a means to understand the perceptual and behavioral performance of people with low vision.

Studies that compared performance between sighted and low-vision participants can use VR headsets to make use of the high degree of experimental control and task flexibility that a virtual environment affords (e.g., [36]). While the previous simulation was tested via first-person perspective on a computer monitor, VR headsets allow for data collection in a fully simulated 3D environment. Using an Oculus Rift CV1 headset, people with central and peripheral vision loss were tasked with interacting in a simulated bank environment. Tasks in the experiment included reading text, identifying objects, navigation, and avoiding obstacles. Compared to sighted controls, low vision participants took twice as long to complete tasks in VR. People with peripheral vision loss took longer to complete tasks compared to people with central vision loss [36].

Previously, Geringswald and colleagues [34] found that people with low vision did not benefit from contextual cueing. In a follow-up study, Pollman and Geringswald [83] tested only sighted participants on a visual search task using realistic scenes. Sighted participants were divided into three groups (sighted, scotoma, and tunnel vision) and
instructed to locate a cup inside a room. A cueing effect was demonstrated in this study with sighted participants performing a more realistic task using objects instead of letters for visual search. This suggests that contextual cueing could potentially enhance visual search performance, this specific method, however, may only be helpful for training people with vision loss in tasks that are meaningful [83].

5.2.3 Common Limitations. Whereas most studies used sighted controls to predict patient outcomes, our analysis suggests that there are a lack of studies using simulations with BLV. Many simulations that replicate low-vision conditions experienced by patients are done by testing sighted controls, but there are no best practices for this technique. Nonelectronic simulation lenses and goggles have been used extensively to study low vision conditions, but these experiments fail to justify how their simulation is comparable to what people with low vision experience. Training BLV with HMDs to improve mobility is promising, but requires standardization in order to be adopted by vision rehabilitation specialists. Experiments that highlight improvements in functional vision (rather than improvements in acuity only) are more likely to play a role in the development of assistive technology.

5.3 Prosthetic Vision in XR

XR technology has not only been used to study visual perception in people with low vision but also in blind people whose vision was restored with a visual neuroprosthesis (“bionic eye”) [28]. These devices send visual input acquired via an external camera to a microstimulator that is implanted in the eye or the brain, which decodes the visual information and stimulates the visual system with electrical current to evoke visual percepts (“phosphenes”). Existing bionic eyes generally provide an improved ability to localize high-contrast objects and perform basic orientation & mobility tasks.

Despite their potential to restore vision to people living with incurable blindness, the number of bionic eye users in the world is still relatively small (∼500 retinal prostheses implanted to date). To investigate functional recovery and experiment with different implant designs, researchers have therefore been developing XR prototypes that rely on simulated prosthetic vision (SPV). The classical method relies on sighted subjects wearing a VR headset, who are then deprived of natural viewing and only perceive phosphenes displayed in the HMD. This viewing mode has been termed “transformative reality” [66, 67] as opposed to “altered reality” which is typically used to describe SLV approaches [5]. This allows sighted participants to “see” through the eyes of the bionic eye user, taking into account their head and/or eye movements as they explore a virtual environment [51].

Fig. 4. Overview of Prosthetic Vision XR studies (n = 55). Studies were categorized based on XR technology used (monitor-based, VR-based, or AR-based), experimental tasks studied (low-level visual function testing; letter, word, and object recognition; spatial cognition, orientation, and mobility), level of immersion considered (viewing stimuli on a monitor, viewing stimuli in an HMD thus incorporating head and/or eye movements, and allowing participants to walk around), and the level of neurobiological detail incorporated (implausible; some detail; detailed model of the response properties of neural tissue).
The distribution of prosthetic vision studies that employ XR is shown in Fig. 4. These include publications that study behavioral performance in various experimental tasks (low-level visual function testing: $n = 7$; object recognition, reading, and visual search: $n = 31$; spatial cognition, orientation, and mobility: $n = 17$), offering varying levels of immersion (viewing stimuli on a screen: $n = 8$; viewing stimuli through an HMD: $n = 36$; interacting with and walking around a virtual environment: $n = 11$) and neurobiological plausibility (none: $n = 48$; some neurobiological detail: $n = 3$; detailed model of the response properties of neural tissue: $n = 4$).

In the following subsections, we will briefly summarize the findings of recent prosthetic vision studies and highlight some common limitations.

5.3.1 Studying Visual Perception and Behavior. A common application of SPV is to assess the impact of different stimulus and model parameters (e.g., phosphene size, flicker rate) on measures of visual acuity. Stimuli for these low-level visual function tests were often presented on monitors [65, 102] or in HMDs [16, 111]. Some studies also tested the influence of field of view (FOV) [86, 94] and eye gaze compensation [98] on acuity.

However, the majority of studies focused on slightly more complex tasks such as letter [119], word [30], face [18, 22], and object recognition [69, 104, 118]. In most setups, participants would view SPV stimuli in a conventional VR HMD, but some studies also relied on smart glasses to present SPV in AR. A notable example is the work by Ho et al. [41], who used AR glasses to simulate the artificial vision provided by the PRIMA subretinal implant [64]. This device was developed for people with geographic atrophy as commonly experienced with AMD. Ho and colleagues therefore had to develop a setup that would allow for the combination of SPV in the macula and natural vision in the periphery.

Lastly, an increasing number of studies are focusing on spatial cognition tasks, such as obstacle avoidance [25, 113, 114] and wayfinding [101]. By design, these tasks require a more immersive setup that allow for the incorporation of head/eye movements as well as locomotion.

5.3.2 Visual Augmentation Strategies. A popular trend for Prosthetic Vision in XR is the experimentation with novel augmentation strategies that can aid scene understanding. One approach is to use computer vision to enhance certain image features or regions of interest, at the expense of discarding less important or distracting information. Various studies have explored strategies based on visual saliency [81, 89], background subtraction and scene retargeting [ ], and depth mapping to highlight nearby obstacles [50, 60, 72]. In one notable study, McCarthy and colleagues [72] used an RGB-D camera mounted on a pair of AR glasses to augment the visual scene with depth information. They showed that this strategy could reduce collisions in a hallway obstacle course even in the presence of low-contrast trip hazards.

5.3.3 Visual Rehabilitation. Another exciting avenue is the use of XR platforms for visual rehabilitation of real bionic eye users. Although companies such as Second Sight Medical Products (the developers of the Argus II Retinal Prosthesis System [68]) provide training by low-vision specialists, there is currently no standardized procedure even across different Argus II implantation centers. Rachitskaya and colleagues [85] therefore developed a Computer-Assisted Rehabilitation Environment (CAREN), which consists of a 10-camera motion capture system, D-Flow control software with a 180° curved projection screen, a 6-degrees-of-freedom motion platform, and a treadmill. For safety, participants donned a harness, had access to handrails on the treadmill, and were accompanied by a physical therapist. In their pilot study [85], the authors first replicated some of the commonly employed visual function tests (e.g., square localization, grating visual acuity, and direction-of-motion discrimination), before moving on to gait assessment, postural stability, and walking speed during basic orientation & mobility tasks. In the future, this platform could be used as a safe environment where bionic eye users can hone their visual skills.
5.3.4 **Common Limitations.** A major outstanding challenge is predicting what people “see” when they use their devices. Most of the studies above relied on the so-called “scoreboard” method to render phosphenes, which assumes that each phosphene acts as a small independent light source, analogous to the images projected on the light bulb arrays of some sports stadium scoreboards [24]. However, a growing body of evidence suggests that the vision generated by current visual prostheses is “fundamentally different” from natural vision [26], with interactions between implant technology and the neural tissue degrading the quality of the generated artificial vision [8, 29]. It is therefore unclear how the findings of most SPV studies would translate to real bionic eye users. Only a handful of studies have incorporated a great amount of neurophysiological detail into their setup [48, 94, 102, 104], only two of which [94, 104] relied on an established and psychophysically evaluated model of SPV.

In addition, the level of immersion offered by most Prosthetic Vision XR studies was relatively low, with most studies simply presenting simulated stimuli on a screen. However, most current prostheses provide a very limited FOV; for example, the artificial vision generated by Argus II [68], the most widely adopted retinal implant thus far, is restricted to 10 × 20 degrees of visual angle. This requires users to scan the environment with strategic head movements while trying to piece together the information [26]. Furthermore, Argus II does not take into account the eye movements of the user when updating the visual scene, which can be disorienting for the user. Ignoring these HCI aspects of bionic vision can result in unrealistic predictions of prosthetic performance, sometimes even exceeding theoretical acuity limits (as pointed out by [17]). To provide realistic estimates of prosthetic performance, future SPV studies should therefore aim to provide an appropriate level of immersion.

6 **OPEN CHALLENGES & FUTURE DIRECTIONS**

XR technology holds great potential to enhance the vision and improve the quality of life of people who are blind or have low vision, either as a component in existing aids or as a standalone aid to provide accessible visual information to the user. However, to realize the full potential of XR, a number of fundamental issues need to be addressed:

- **Lack of Ecological Validity:** While XR technologies were successful in improving visual function such as clinical measurements (e.g., acuity, contrast sensitivity, visual field), object recognition, and mobility, there is currently no robust evidence that they can improve mobility in practical real-world tasks [72, 115]. Many SLV studies that involve sighted people base their impairment conditions off of rudimentary approximations of BLV rather than conditions grounded in patient data [47]. Most gaze-contingent scotoma simulations for sighted people are gray masks, whereas many BLV with central vision loss are not aware of their scotoma [103]. Studies that have used simulation lenses or goggles would benefit from more realistic models of low vision [6, 23, 59, 92].

- **Lack of BLV Involvement:** The majority of the here reviewed research has mainly focused on technical developments such as exploring different computer vision and enhancement techniques (e.g., [42, 72, 100, 117]) and reporting quantitative measures such as mobility efficiency and errors, obstacle detection rates, and clinical visual measurements [6, 40, 43]. Less emphasis has been placed on understanding the usability and suitability of these aids in people with different levels of residual vision and underlying conditions. The majority of the studies did not report participants’ opinions and feedback regarding the visual augmentations which determine the success and usability of the aids. Additionally, most of the studies failed to involve potential end users at the initial design stage to capture their specific requirements. Instead, they relied on the researchers’ perception of the end user’s needs, which may be insufficient due to significant differences in visually guided behavior between sighted individuals and BLV [32, 107, 108].

Manuscript submitted to ACM
• Adoption by End Users: Despite progress, none of the proposed devices have found widespread adoption. Older adults have more challenges when using new technology [54]. Assistive technology typically comes with a set of instructions for the user but comprehensive training requires a rehabilitation specialist to be physically present [13]. In addition, devices that function well outdoors have limited indoor navigation capabilities, therefore limiting the number of cases in which it could be used[108]. Another reason for poor adoption rate could be that most XR prototypes do not yet exist in an appropriate form factor, as most end users prefer a compact device that looks similar to a regular pair of glasses and uses buttons as an inconspicuous mode of interaction [77]. One type of device may be better for work productivity while another device could be preferred for leisurely activities [77, 93].

In conclusion, our systematic review has highlighted that XR technology is useful for studying BLV behavior, but challenges still remain. VR and AR technology are still relatively new and would benefit from standard practices of accessibility and usability [49], preferably integrating BLV end users at all stages of the design process [14, 97]. While XR is promising as a new technology, not all design aspects have to be modernized. For example, most people with low vision prefer tactile buttons over voice or hand gestures for smart glasses [77]. The field made a step in the right direction, but there is much work needed to fully understand how BLV end users will benefit from modern assistive technologies.

REFERENCES

[1] Douglas A Addleman, Gordon E Legge, and Yuhong Jiang. 2020. Simulated central vision loss impairs implicit location probability learning. Cortex (2020). https://doi.org/10.1016/j.cortex.2021.02.009 Publisher: PsyArXiv.
[2] Anastassios Nikolaos Angelopoulos, Hossein Ameri, Debbie Mitra, and Mark Humayun. 2019. Enhanced Depth Navigation Through Augmented Reality Depth Mapping in Patients with Low Vision. Scientific Reports 9, 1 (2019), 11230. https://doi.org/10.1038/s41598-019-47397-w
[3] Halim Cagri Ates. 2015. Immersive Simulation of Visual Impairments Using a Wearable See-through Display. In 7EII ’15: Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction. https://doi.org/10.1145/2677199.2680551
[4] Shiri Azenkot and Yuhang Zhao. 2017. Designing smartglasses applications for people with low vision. In ACM SIGACCESS Accessibility and Computing. 19–24. https://doi.org/10.1145/3167902.3167905 Publisher: ACM New York, NY, USA.
[5] Min Bao and Stephen A. Engel. 2019. Augmented Reality as a Tool for Studying Visual Plasticity: 2009 to 2018. Current Directions in Psychological Science 28, 6 (Dec. 2019), 574–580. https://doi.org/10.1177/0963721419862290 Publisher: SAGE Publications Inc.
[6] Erica M. Barhorst-Cates, Kristina M. Rand, and Sarah H. Creem-Regehr. 2017. Let me be your guide: physical guidance improves spatial learning for older adults with simulated low vision. Experimental Brain Research 235, 11 (2017), 3307–3317. https://doi.org/10.1007/s00221-017-5063-8
[7] Erica M. Barhorst-Cates, Kristina M. Rand, and Sarah H. Creem-Regehr. 2019. Navigating with peripheral field loss in a museum: learning impairments due to environmental complexity. Cognitive Research: Principles and Implications 4, 1 (Oct. 2019), 41. https://doi.org/10.1186/s41235-019-0189-9
[8] Michael Beyeler, Deryani Nanduri, James D. Weiland, Ariel Rokem, Geoffrey M. Boynton, and Ione Fine. 2019. A model of ganglion axon pathways accounts for percepts elicited by retinal implants. Scientific Reports 9, 1 (June 2019), 1–16. https://doi.org/10.1038/s41598-019-45416-4
[9] Alexander P. Boone, Xinyi Gong, and Mary Hegarty. 2018. Sex differences in navigation strategy and efficiency. Memory & Cognition 46, 6 (Aug. 2018), 909–922. https://doi.org/10.3758/s13441-018-0811-y
[10] Matthew Bronstad, Alex R. Bowers, Amanda Albu, Robert Goldstein, and Eli Peli. 2013. Driving with central field loss I: effect of central scotomas on responses to hazards. JAMA ophthalmology 131, 3 (March 2013), 303–309. https://doi.org/10.1001/jamaophthalmol.2013.1443
[11] Flon E. Brown, Janice Sutton, Ho M. Yuen, Dylan Green, Spencer Van Dorn, Terry Braun, Angela J. Cree, Stephen R. Russell, and Andrew J. Lotery. 2019. A novel, wearable, electronic visual aid to assist those with reduced peripheral vision. PloS One 14, 10 (2019), e0223755. https://doi.org/10.1371/journal.pone.0223755
[12] Emeline Brulé, Brianna J. Tomlinson, Oussama Metatla, Christophe Jouffrais, and Marcos Serrano. 2020. Review of Quantitative Empirical Evaluations of Technology for People with Visual Impairments. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376749
[13] Marloes C. Burggraaff, Ruth M. A. van Nisp, Bart J. M. Melis-Dankers, and Ger H. M. B. van Rens. 2010. Effects of standard training in the use of closed-circuit televisions in visually impaired adults: design of a training protocol and a randomized controlled trial. BMC health services research 10 (March 2010), 62. https://doi.org/10.1186/1472-6963-10-62

Manuscript submitted to ACM
Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review

38 Adrian H. Hoppe, Julia K. Anken, Thorsten Schwarz, Rainer Stiefelhagen, and Florian van de Camp. 2020. CLEVR: A Customizable Interactive Learning Environment for Users with Low Vision in Virtual Reality. In The 22nd International ACM SIGACCESS Conference on Computers and Accessibility. 1–4. https://doi.org/10.1145/337625.3418009

39 Shamim A. Haji, Kumar Sambhav, Sandeep Grover, and Kakarla V. Chalam. 2015. Evaluation of the iPad as a low vision aid for improving reading ability. Clinical Ophthalmology (Auckland, N.Z.) 9 (2015), 17–20. https://doi.org/10.2147/OPTH.S73193

40 Stephen L. Hicks, Iain Wilson, Louwai Muhammed, John Worsfold, Susan M. Downes, and Christopher Kernard. 2013. A depth-based head-mounted visual display to aid navigation in partially sighted individuals. PloS One 8, 7 (2013), e67695. https://doi.org/10.1371/journal.pone.0067695

41 Elton Ho, Jack Boffa, and Daniel Palanker. 2019. Performance of complex visual tasks using simulated prosthetic vision via augmented-reality glasses. Journal of Vision 19, 13 (2019), 22. https://doi.org/10.1167/19.13.22

42 Katsuya Hommaru and Jiro Tanaka. 2020. Walking Support for Visually Impaired Using AR/MR and Virtual Braille Block. In International Conference on Human-Computer Interaction. Springer. 336–354. https://doi.org/10.1007/978-3-030-49282-3_24

43 Kevin E. Houston, Alex R. Bowers, El Peli, and Russell L. Woods. 2018. Peripheral Prisms Improve Obstacle Detection during Simulated Walking for Patients with Left Hemispatial Neglect and Hemianopia. Optometry and Vision Science: Official Publication of the American Academy of Optometry 95, 9 (2018), 795–804. https://doi.org/10.1097/OPX.0000000000001280

44 Hein Min Htike, Tom H. Margrain, Yu-Kun Lai, and Parisa Eslambolchilar. 2020. Ability of Head-Mounted Display Technology to Improve Mobility in People With Low Vision: A Systematic Review. Translational Vision Science & Technology 9, 10 (Sept. 2020). https://doi.org/10.1167/tvst.9.10.26

45 Jonathan Huang, Max Knatateder, Matt J. Dunn, Wojciech Jarosz, Xing-Dong Yang, and Emily A. Cooper. 2019. An augmented reality sign-reading assistant for users with reduced vision. PloS One 14, 1 (2019), e212630. https://doi.org/10.1371/journal.pone.0212630

46 Alex D. Hwang and Eli Peli. 2014. An augmented-reality edge enhancement application for Google Glass. Optometry and Vision Science: Official Publication of the American Academy of Optometry 91, 8 (Aug. 2014), 1021–1030. https://doi.org/10.1097/OPX.0000000000000526

47 Pete R. Jones, Tamás Somoskeöy, Hugo Chow-Wing-Bom, and David P. Crabb. 2020. Seeing other perspectives: evaluating the use of virtual and augmented reality to simulate visual impairments (OpenViewSim). NPJ digital medicine 3, 2020. https://doi.org/10.1038/s41746-020-0242-6

48 Horace Josh, Collette Mann, Lindsay Kleeman, and Wen Lin Dennis Lui. 2013. Psychophysics testing of bionic vision image processing algorithms using an FPGA Hatpack. In 2013 IEEE International Conference on Image Processing. 1550–1554. https://doi.org/10.1109/ICIP.2013.6738319 ISNN: 2381-8549

49 Vaishnav Kameswaran, Alexander J. Fiammace, Melanie Kneisel, Amy Karlson, Edward Currall, and Meredith Ringel Morris. 2020. Understanding In-Situ Use of Commonly Available Navigation Technologies by People with Visual Impairments. In The 22nd International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS ’20). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/337625.3416995

50 Arathy Kartha, Roksana Sadegh, Michael P. Barry, Chris Bradley, Paul Gibson, Avi Caspi, Arup Roy, and Gislin Dagnelie. 2020. Prosthetic Visual Performance Using a Disparity-Based Distance-Filtering System. Translational Vision Science & Technology 9, 12 (Nov. 2020), 27–27. https://doi.org/10.1167/tvst.9.12.27 Publisher: The Association for Research in Vision and Ophthalmology.

51 Justin Kasowski, Nathan Wu, and Michael Beyeler. 2021. Towards Immersive Virtual Reality Simulations of Bionic Vision. In Augmented Humans Conference 2021 (AH’21). Association for Computing Machinery, New York, NY, USA, 313–315. https://doi.org/10.1145/3458709.3459003

52 Stacy M. Kelly and Derrick W. Smith. 2011. The Impact of Assistive Technology on the Educational Performance of Students with Visual Impairments: A Synthesis of the Research. Journal of Visual Impairment & Blindness 105, 2 (Feb. 2011), 73–83. https://doi.org/10.1177/0145482X1110500205 Publisher: SAGE Publications Inc.

53 Miyoung Kwon, Hinny S. Nandy, and Bosco S. Tjan. 2013. Rapid and persistent adaptability of human oculomotor control in response to simulated central vision loss. Current biology: CB 23, 17 (Sept. 2013), 1663–1669. https://doi.org/10.1016/j.cub.2013.06.056

54 Miyoung Kwon, Chaithanya Ramachandra, Premmandhini Satgunam, Bartlett W. Mel, Eli Peli, and Bosco S. Tjan. 2012. Contour enhancement benefits older adults with simulated central field loss. Optometry and Vision Science: Official Publication of the American Academy of Optometry 89, 9 (Sept. 2012), 1374–1384. https://doi.org/10.1097/OPX.0b013e3182678e52

55 Florian Lang, Albrecht Schmidt, and Tonja Machulla. 2020. Augmented Reality for People with Low Vision: Symbolic and Alphanumeric Representation of Information. In International Conference on Computers Helping People with Special Needs. Springer. 146–156. https://doi.org/10.1007/978-3-030-58976-3_19

56 Keziah Latham, Sam Waller, and James Schaitel. 2011. Do best practice guidelines improve the legibility of pharmacy labels for the visually impaired? Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists) 31, 3 (May 2011), 275–282. https://doi.org/10.1111/j.1475-1313.2010.00816.x

57 Jien Lee and Makoto Itoh. 2020. Effects of driver compensatory behaviour on risks of critical pedestrian collisions under simulated visual field defects. PloS One 15, 4 (2020), e0231130. https://doi.org/10.1371/journal.pone.0231130 Manuscript submitted to ACM
[60] Paulette Lieby, Nick Barnes, Chris McCarthy, Nianjun Liu, Hugh Dennett, Janine G. Walker, Viorica Botea, and Adele F. Scott. 2011. Substituting depth for intensity and real-time phosphene rendering: visual navigation under low vision conditions. In Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2011. 8017–8020. https://doi.org/10.1109/IEMBS.2011.6091977

[61] Jih-Hsuan Tammy Lin. 2017. Fear in virtual reality (VR): Fear elements, coping reactions, immediate and next-day fright responses toward a survival horror zombie virtual reality game. Computers in Human Behavior 72 (July 2017), 350–361. https://doi.org/10.1016/j.chb.2017.02.057

[62] Kai Wen Lin, Tak Kit Lau, Chi Ming Cheuk, and Yunhui Liu. 2012. A wearable stereo vision system for visually impaired. In 2012 IEEE International Conference on Mechatronics and Automation. 1423–1428. https://doi.org/10.1109/ICMA.2012.6284345 ISSN: 2152-744X

[63] Rong Liu and MiYoung Kwon. 2016. Integrating oculomotor and perceptual training to induce a pseudofovea: A model system for studying central vision loss. Journal of Vision 16, 6 (2016), 10. https://doi.org/10.1167/16.6.10

[64] H. Lorach, G. Goetz, R. Smith, X. Lei, Y. Mandel, T. Kamins, K. Mathieson, P. Husie, J. Harris, A. Sher, and D. Palanker. 2015. Photovoltaic restoration of sight with high visual acuity. Nat Med 21, 5 (May 2015), 476–82. https://doi.org/10.1038/nm.3851

[65] Yanyu Lu, Panpan Chen. Ying Zhao, Jinrui Shi, Quushi Ren, and Xinyu Chai. 2012. Estimation of simulated phosphene size based on tactile perception. Artificial Organs 36, 1 (Jan. 2012), 115–120. https://doi.org/10.1111/j.1525-1594.2011.01288.x

[66] Wen Lin Dennis Lui, Damien Browne, Lindsay Kleeman, Tom Drummond, and Wai Ho Li. 2011. Transformative reality: Augmented reality for visual prostheses. In 2011 10th IEEE International Symposium on Mixed and Augmented Reality. 253–254. https://doi.org/10.1109/ISMAR.2011.6092402

[67] Y. H. Luo and L. da Cruz. 2016. The Argus(R) II Retinal Prosthesis System. Prog Retin Eye Res 50 (Jan. 2016), 89–107. https://doi.org/10.1016/j.preteyeres.2015.09.003

[68] Marc J.-M. Maé, Valérien Guivarch, Grégoire Denis, and Christophe Jouffrais. 2015. Simulated Prosthetic Vision: The Benefits of Computer-Based Object Recognition and Localization. Artificial Organs 39, 7 (July 2015), E102–113. https://doi.org/10.1111/aor.12476

[69] Kanak Manjari, Madhushi Verma, and Gaurav Singal. 2020. A survey on Assistive Technology for visually impaired. Internet of Things 11 (Sept. 2020), 100188. https://doi.org/10.1016/j.iot.2020.100188

[70] Sergio Mascetti, Dragan Ahmetovic, Andrea Gerino, Cristian Bernareggi, Mario Busso, and Alessandro Rizzi. 2016. Robust traffic lights detection with robotic sensing. In Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2012. 304–307. https://doi.org/10.1109/EMBC.2012.6345929

[71] Tetsuya Oda, Hiroaki Shirai, Kyohei Toyoshima, Masaharu Hirota, Ryo Ozaki, and Kengo Katayama. 2020. VR Application for Supporting Object Recognition Considering Eye in Low Vision. In Proceedings of the 2020 8th International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2020, 16, 6 (2020), 1–4. https://doi.org/10.1109/EMBS.2020.9137218

[72] Elizabeth W. Loder, Evan Mayo-Wilson, Steve McDonald, Luke A. McGuinness, Lesley A. Stewart, James Thomas, Andrea C. Tricco, Vivian A. Tetzlaff, Elie A. Akl, Sue E. Brennan, Roger Chou, Julie Glanville, Jeremy M. Grimshaw, Asbjørn Hróbjartsson, Manoj M. Lalu, Hugh Dennett, Janine G. Walker, Viorica Botea, and Adele F. Scott. 2011. Substituting household objects with the artificial vision therapy system by integration with thermal sensor. British Journal of Ophthalmology 104, 12 (Dec. 2020), 1730–1734. https://doi.org/10.1136/bjophthalmol-2019-315513 Publisher: BMJ Publishing Group Ltd Section: Clinical science.

[73] Michael Meehan, Brent Insko, Mary Whitten, and Frederick P. Brooks. 2002. Physiological measures of presence in stressful virtual environments. ACM Transactions on Graphics 21, 3 (July 2002), 645–652. https://doi.org/10.1145/566554.566630

[74] Sandra R. Montezuma, Susan Y. Sun, Arup Roy, Avi Caspi, Jessy D. Dorn, and Yingchen He. 2020. Improved localisation and discrimination of heat perception. Artificial Organs 44, 5 (2020), 597–599. https://doi.org/10.1111/aor.13957

[75] Paulette Lieby, Nick Barnes, Chris McCarthy, Nianjun Liu, Hugh Dennett, Janine G. Walker, Viorica Botea, and Adele F. Scott. 2011. Substituting depth for intensity and real-time phosphene rendering: visual navigation under low vision conditions. In Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2011. 8017–8020. https://doi.org/10.1109/IEMBS.2011.6091977

[76] Elliott Morris, Aaron P. Johnson, J.-A. Mariner, and Walter Wittich. 2017. Assessment of the Apple iPad as a low-vision reading aid. Eye (London, England) 31, 6 (June 2017), 865–871. https://doi.org/10.1038/eye.2016.309

[77] Karst M.P. Hoogsteen, Sjoonke A. Oosting, Bea L.P.A. Steenbekkers, and Sarit F.A. Szpiro. 2020. Functionality versus Inconspicuousness: Attitudes of People with Low vision towards OST Smart Glasses. In The 22nd International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS ’20). Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3373825.3418102

[78] C. D. Mulrow. 1994. Systematic Reviews: Rationale for systematic reviews. BMJ 309, 6954 (Sept. 1994), 597–599. https://doi.org/10.1136/bmj.309.6954.597 Publisher: British Medical Journal Publishing Group Section: Education and debate.

[79] Tetsuya Oda, Hiroaki Shirai, Kyohei Toyoshima, Masaharu Hirota, Ryo Ozaki, and Kengo Katayama. 2020. VR Application for Supporting Object Recognition Considering Eye in Low Vision. In Proceedings of the 2020 8th International Conference of the IEEE Engineering in Medicine and Education Technology Society. 295–299. https://doi.org/10.1109/3395245.3396232

[80] Matthew J. Page, Joanne E. McKenzie, Patrick M. Bossuyt, Isabelle Routon, Tammy C. Hoffmann, Cynthia D. Mulrow, Larissa Shameer, Jennifer M. Tetzlaff, Elie A. Akl, Sue E. Brennan, Roger Chou, Julie Glanville, Jeremy M. Grimshaw, Asbjørn Hróbjartsson, Manoj M. Lalu, Tianjing Li, Hugh Dennett, Janine G. Walker, Viorica Botea, and Adele F. Scott. 2011. Substituting household objects with the artificial vision therapy system by integration with thermal sensor. British Journal of Ophthalmology 104, 12 (Dec. 2020), 1730–1734. https://doi.org/10.1136/bjophthalmol-2019-315513 Publisher: BMJ Publishing Group Ltd Section: Clinical science.

[81] Neeti Parikh, Laurent Itti, Mark Humayun, and James Weiland. 2013. Performance of visually guided tasks using simulated prosthetic vision and saliency-based cues. Journal of Neural Engineering 10, 2 (April 2013), 026017. https://doi.org/10.1088/1741-2560/10/2/026017

Manuscript submitted to ACM
Furthering Visual Accessibility with Extended Reality (XR): A Systematic Review

[82] Marco Pasch, Nadia Bianchi-Berthouze, Betsys van Dijk, and Anton Nijholt. 2009. Immersion in Movement-Based Interaction. In Intelligent Technologies for Interactive Entertainment (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering). Anton Nijholt, Dennis Reidsma, and Hendri Hordorp (Eds.). Springer, Berlin, Heidelberg, 169–180. https://doi.org/10.1007/978-3-642-02355-6_16

[83] Stefan Pollmann, Franziska Geringwold, Ping Wei, and Eleonora Forracin. 2020. Intact Contextual Cueing for Search in Realistic Scenes with Simulated Central or Peripheral Vision Loss. Translational Vision Science & Technology 9, 8 (July 2020), 15. https://doi.org/10.1167/tvst.9.8.15

[84] Shrinivas Pandilk, HuaiQi Yi, Rui Liu, Eli Peli, and Gang Luo. 2017. Magnifying Smartphone Screen Using Google Glass for Low-Vision Users. IEEE transactions on neural systems and rehabilitation engineering: a publication of the IEEE Engineering in Medicine and Biology Society 25, 1 (2017), 52–61. https://doi.org/10.1109/TNSRE.2016.2540602

[85] Aleksandra Rachitskaya, Alex Yuan, Sara Davidson, Matthew Streicher, Meghan DeBenedictis, Anson B. Rosenfeldt, and Jay Alberts. 2020. Computer-Assisted Immersive Visual Rehabilitation in Argus II Retinal Prosthesis Recipients. Ophthalmology: Retina 4, 6 (2020), 613–619. https://doi.org/10.1016/j.orret.2019.11.007

[86] Melani Sanchez Garcia, Ruben Martinez-Cantin, Jesus Bermudez-Cameo, and Jose Jesus Guerrero-Campo. 2020. Influence of field of view in visual prostheses design: Analysis with a VR system. Journal of Neural Engineering (Sept. 2020). https://doi.org/10.1088/1741-2552/abb9be

[87] Lucía Santamaría and Helena Mihaljevic. 2018. Comparison and benchmark of name-to-gender inference services. PeerJ Computer Science 4 (July 2018), e156. https://doi.org/10.7717/peerj-cs.156 Publisher: PeerJ Inc.

[88] Alexandra Sipatchin, Siegfried Wahl, and Katharina Rifi. 2020. Eye-tracking for low vision with virtual reality (VR): testing status quo usability of the HTC Vive Pro Eye. bioRxiv (2020). https://doi.org/10.1101/2020.07.29.220889 Publisher: Cold Spring Harbor Laboratory.

[89] Ashley Stacey, Yi Li, and Nick Barnes. 2011. A salient information processing system for bionic eye with application to obstacle avoidance. In Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2011. 516–519. https://doi.org/10.1109/EMBS.2011.6091267

[90] Lee Stearns, Victor DeSouza, Jessica Yin, Leah Findlater, and Jon E. Froehlich. 2017. Augmented reality magnification for low vision users with the microsoft hololens and a finger-worn camera. In Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility. 361–362. https://doi.org/10.1145/3135255.3134812

[91] Lee Stearns, Leah Findlater, and Jon E. Froehlich. 2018. Design of an augmented reality magnification aid for low vision users. In Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility. 28–39.

[92] Margaret R. Tarampi, Sarah H. Creem-Regehr, and William B. Thompson. 2010. Intact spatial updating with severely degraded vision. Attention, Perception & Psychophysics 72, 1 (Jan. 2010), 23–27. https://doi.org/10.3758/APP.72.1.23

[93] John J. Taylor, Rachel Bambrick, Andrew Brand, Nathan Bray, Michelle Dutton, Robert A. Harper, Zoe Hoare, Barbara Ryan, Rhiannon T. Edwards, Heather Waterman, and Christine Dickinson. 2017. Effectiveness of portable electronic and optical magnifiers for near vision activities in low vision: a randomised crossover trial. Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists) 37, 4 (2017), 370–384. https://doi.org/10.1111/op.12379

[94] Jacob Thomas Thorn, Enrico Migliorini, and Diego Ghersi. 2020. Virtual reality simulation of epiretinal stimulation highlights the relevance of the visual angle in prosthetic vision. Journal of Neural Engineering (2020). https://doi.org/10.1088/1741-2552/abb8bc Publisher: IOP Publishing.

[95] Lauren Thévin, Carine Briant, and Anke M Brock. 2020. X-Road: Virtual Reality Glasses for Orientation and Mobility Training of People with Visual Impairments. ACM Transactions on Accessible Computing (TACCESS) 13, 2 (2020), 1–47. https://doi.org/10.1145/3377879 Publisher: ACM New York, NY, USA.

[96] Ya Tian, Yong Liu, and Jindong Tan. 2013. Wearable navigation system for the blind people in dynamic environments. In 2013 IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems. 153–158. https://doi.org/10.1109/CYBER.2013.6705437

[97] Gareth W. Tigwell. 2021. Nuanced Perspectives Toward Disability Simulations from Digital Designers, Blind, Low Vision, and Color Blind People. In 20th International ACM SIGACCESS Conference on Computers and Accessibility. 28–39.

[98] Margaret R. Tarampi, Sarah H. Creem-Regehr, and William B. Thompson. 2010. Intact spatial updating with severely degraded vision. Attention, Perception & Psychophysics 72, 1 (Jan. 2010), 23–27. https://doi.org/10.3758/APP.72.1.23

[99] John J. Taylor, Rachel Bambrick, Andrew Brand, Nathan Bray, Michelle Dutton, Robert A. Harper, Zoe Hoare, Barbara Ryan, Rhiannon T. Edwards, Heather Waterman, and Christine Dickinson. 2017. Effectiveness of portable electronic and optical magnifiers for near vision activities in low vision: a randomised crossover trial. Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists) 37, 4 (2017), 370–384. https://doi.org/10.1111/op.12379

[100] Jacob Thomas Thorn, Enrico Migliorini, and Diego Ghersi. 2020. Virtual reality simulation of epiretinal stimulation highlights the relevance of the visual angle in prosthetic vision. Journal of Neural Engineering (2020). https://doi.org/10.1088/1741-2552/abb8bc Publisher: IOP Publishing.

[101] Lauren Thévin, Carine Briant, and Anke M Brock. 2020. X-Road: Virtual Reality Glasses for Orientation and Mobility Training of People with Visual Impairments. ACM Transactions on Accessible Computing (TACCESS) 13, 2 (2020), 1–47. https://doi.org/10.1145/3377879 Publisher: ACM New York, NY, USA.

[102] Ya Tian, Yong Liu, and Jindong Tan. 2013. Wearable navigation system for the blind people in dynamic environments. In 2013 IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems. 153–158. https://doi.org/10.1109/CYBER.2013.6705437

[103] Victor Vergnieux, Marc J.-M. Macé, and Christophe Jouffrais. 2014. Wayfinding with simulated prosthetic vision: performance comparison with regular and structure-enhanced renderings. In Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, Vol. 2014. 2585–2588. https://doi.org/10.1109/EMBC.2014.6944151

[104] Malena Vurro, Anne Marie Crowell, and John S. Pezaris. 2014. Simulation of thalamic prosthetic vision: reading accuracy, speed, and acuity in sighted humans. Frontiers in Human Neuroscience 8 (2014), 816. https://doi.org/10.3389/fnhum.2014.00816

Manuscript submitted to ACM
