Head-mounted Devices for Low Vision: A Review

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Abstract: Head-mounted devices (HMDs) are wearable electronic tools designed to augment the visual experience of low-vision patients who have a decrease in vision not improved by refractive correction. They do so by addressing various principles of visual enhancement, including magnification, illumination, increased field of view, and contrast sensitivity enhancement, among others. Since the introduction of the first HMD 3 decades ago, advancements in technology have made these devices more lightweight and practical for everyday use. More sophisticated features have been developed, including augmented reality, virtual reality, text-to-speech, and blind spot remapping. However, despite these advancements, HMDs still face a host of challenges, including cost, customizability to specific patient factors, and social stigma. In this paper, we present a broad overview of HMDs, review major products available commercially, and discuss the challenges and future directions for this rapidly growing field.

Key Words: head-mounted device, augmented reality, virtual reality, low vision

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INTRODUCTION

Visual impairment, including blindness and low vision, refers to a decrease in visual acuity or visual field, which impairs someone's ability to perform daily activities of living. While some causes of visual impairment arise from the central nervous system, the majority arise due to intraocular pathologies. The human eye is a complex optical system which requires the precise coordination of multiple anatomic components, and deficiencies in any one part of the system can lead to visual impairment.

While many causes of visual impairment are currently treatable, many other causes are not correctable by refractive, medical, or surgical means. These patients are said to have low vision. The World Health Organization defines low vision as a best-corrected visual acuity between 20/70 and 20/400 or a visual field of 20 degrees or less.[1] Blindness is defined as a best-corrected visual acuity worse than 20/400 or a visual field of 10 degrees or less.[1] Quality of vision is also defined by contrast sensitivity—a person's ability to perceive outlines and fine gradations in pattern or shape. Although contrast sensitivity and visual acuity are often correlated, many conditions can have near-normal levels of visual acuity but have significant reductions in color and contrast sensitivity. Deficiencies in contrast sensitivity have been shown to affect mobility, facial recognition, and task performance even when controlled for visual acuity.[2]

While a problem with any one of the eye's components can contribute to low vision, pathologies of the retina and the optic nerve are common culprits. These tissues have limited capacity to regenerate, and damage is often permanent and irreversible. For many conditions, including macular dystrophy, retinitis pigmentosa, glaucoma, and optic neuropathy, medical and surgical treatments to restore vision remain areas of active research. Patients with these conditions have few options for medical therapies and rely on low-vision devices while living with poor vision.

It is well-established that patients with low vision have higher rates of depression and are more likely to fall and suffer injury.[3,4] There can also be financial consequences. According to an analysis by the American Foundation for the Blind, adults with low vision make over $13,000 less than their sighted counterparts and are much less likely to be employed at all—44% compared with 79% of adults with normal vision.[5] On a society-wide scale, the annual cost of vision impairment and blindness in the United States is estimated to be 170 billion dollars.[6]

Given the significant personal and societal costs of low vision, there is substantial interest in developing tools to improve the quality of life of these patients. Such tools seek to maintain the independence of patients with low vision and help ensure they can continue to carry out their tasks of daily living as they age despite low vision. Regardless of visual function, the US population is aging, and reports indicate that $>800{,}000$ elderly patients now live in assisted living facilities, with this number expected to continue to increase until 2040. Thus, aging patients with low vision will have yet another need for assistance. As such, effective tools must address not only visual acuity but multiple other aspects of the visual experience, including contrast sensitivity, visual field, and depth perception, to help patients maintain their ability to carry out basic functions in their day-to-day lives.

Before the technological age, the primary low-vision assistive device was a refractive correction, specifically

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optical magnification. However, magnifiers have several disadvantages, including fixed focal lengths and decreased field of view. Furthermore, conventional magnifiers improve near vision but have limited abilities to improve distance vision or alter contrast. Later, closed-circuit television (CCTV) was developed, using cameras to project magnified images onto a screen. However, CCTV comes with a significant limitation in mobility, confining its use mostly to reading in the home setting.

With further advancements in technology, a new class of low-vision aid, head-mounted devices (HMDs), has been introduced. These wearable devices attempt to provide an enhanced visual experience while addressing the limitations of conventional optical aids. This review will highlight some of the established and emerging HMDs for low vision.

Classification and Principles of Head-mounted Devices

In general, HMDs capture information from the environment via one or more front-facing cameras. Visual data is then run through image-processing software, which presents real-time, enhanced viewing to the user through a variety of techniques, including magnification, autofocusing, contrast or lighting optimization, and text-to-audio conversion. An ideal HMD automates these features as much as possible, limiting the amount of manual input needed to change the visual output. In addition, an HMD should also be comfortable, lightweight, and ergonomic enough to make its use practical in a daily setting.

HMD displays can be classified as monocular, biocular, or binocular.[7] Monocular displays present images to one eye only. An example is the consumer version of Google Glass, which is no longer on the market and featured an optical display mounted above one eye only. Biocular displays present the same image to both eyes. Binocular displays present different images to each eye based on their spatial orientation to the object being viewed. This allows for stereoscopic viewing but represents a greater design challenge, especially as visual impairment is usually asymmetric.[7]

More recently, HMDs with virtual and augmented reality features have been developed.[8] Virtual reality (VR) completely replaces the real visual environment with a simulated environment projected on electronic screens. VR can be advantageous in that it presents a unified, cohesive visual experience, but comes with the considerable expense of severing the user from the natural visual environment, which can lead to safety concerns. Augmented reality (AR), on the other hand, uses see-through displays to preserve a user's natural view of the real world while adding complementary visual information on the screen electronically. AR has the benefit of preserving a visual connection with one's real surroundings but may have the drawback of presenting an overwhelming amount of visual information in one's natural view of the world.

Certain parameters are used to describe the capabilities of HMDs, including resolution, field of view, luminance, color, among others.[7] The first 2 parameters are inextricably linked. Current HMDs cannot yet replicate a normal human field of view, which is roughly 180 degrees. However, given the proximity of HMD screens to the user's eyes, the effective field of view of an HMD is generally much greater than that of a computer screen viewed at a normal working distance. As such, the resolution of an HMD screen, as measured in pixels per degree, must correspondingly be greater to ensure clarity and sharpness. HMDs must also possess a range and versatility of luminance and color to maximize acuity in both photopic and scotopic conditions and conditions requiring contrast.

Low Vision Enhancement System

The first head-mounted low-vision device is the low vision enhancement system (LVES).[9] Introduced in 1994 by a collaborative effort of Johns Hopkins University, NASA, and the Veterans Administration, the LVES is a battery-powered, binocular head-mounted video display that utilizes 3 video cameras and an external video input to provide the user with magnified, contrast-enhanced images. Two orientation cameras on the axis with the user's pupils furnish a 60 degrees binocular field of view, while a "cyclopean" midline camera provides zoom magnification, variable focus, and downward tilt for reading and manual tasks.[9] The LVES also uses a preemphasis spatial filter to increase contrast and help users recognize faces, as well as mapping technology to compensate for central scotomas.

These innovative features of the LVES proved useful to patients in multiple studies. Weckerle et al[10] found that the LVES improved reading, handwriting, walking, and contrast sensitivity in patients with a central scotoma who had a magnification need up to 8x. Ballinger et al[11] demonstrated an improvement in visual acuity of, on average, 6 Snellen lines in both AMD and non-AMD patients using the LVES. Although these results were highly promising, disadvantages of the LVES such as its large size, magnification limitations, and slow auto-focusing speed limited its practical appeal and widespread adoption.[12] However, despite its shortcomings, the LVES opened the door for the development of other HMDs.

Over the past several decades, these HMDs have significantly progressed and undergone major technological advancements due to improvements in camera and display technologies. These technological improvements have made these devices more user-friendly and practical for patients in their everyday lives. Several such devices are reviewed here and briefly summarized in Figure 1.

Jordy

Jordy (Enhanced Vision Systems, Huntington Beach, CA) is a hands-free, head-mounted electronic magnifier with a portable battery pack containing up to eight hours of battery life. Co-developed by New England Low Vision and Blindness and Enhanced Vision and first introduced in 1998, it has gone through several iterations, including a phase-out from the market in 2010 and reintroduction in 2017. Its features include a side hinge that allows for pantoscopic tilt, manual toggling of contrast

Device	Weight	VR/AR	Features
Jordy	227 g	NA	HD autofocus camera Adjustable magnification, brightness control HDMI input for TV viewing
E-Sight	560 g	AR	Camera projection onto two high resolution screens Connectivity with Android, Apple, WiFi, Bluetooth and HDMI Autofocus, image stabilization, zoom and contrast
IrisVision	172 g	VR	Software for scotoma and field of view mapping Autofocus, text to speech, voice control
AceSight	360 g	AR	Semi-transparent display with image capture and magnification Compression of wide visual field into smaller field of view
Oculenz	400 g	AR	Camera with overlay of re-mapped images onto remaining field of view Image stabilization, eye-tracking
Eyedaptic	85 g	AR	Reformulated images with pixel enhancement and remapping of scotomas Image stabilization, contrast enhancement, autozoom

FIGURE 1. Select head-mounted devices and features. AR indicates augmented reality; NA, not applicable; VR, virtual reality.

modes, and an autofocus camera with multiple zoom settings targeting near, intermediate, or far distances up to 66× magnification.[13]

An early study in 2004 by Culham et al[14] compared Jordy to several competitors and optical low vision aids (LVAs). The authors found that Jordy provided better distance visual acuity than all other tested modalities. Jordy and Flipperport provided improved intermediate visual acuity compared with optical LVAs, spectacles, and NuVision. However, Jordy fared worse for near visual acuity in AMD patients compared with optical LVAs, although it performed better for near visual acuity in early-onset macular disease (EOMD) patients.

A 2018 pilot study by Troyer and Dixon[15] found that Jordy provided a larger improvement in distance visual acuity compared with eSight but was the lowest ranked of 3 HMDs based on overall preference/performance. Another recent study in 2023 by Schmidt et al[16] tested Jordy and 3 other HMDs in patients with Stargardt Disease, which causes central vision loss. They found that Jordy improved distance visual acuity and increased reading distance, although it did not improve near visual acuity with high or low contrast. Of note, Jordy was perceived as being the most user-friendly device in the clinic setting, although after at-home trials, Jordy performed below baseline in all tasks.

eSight

Another such device is the eSight Eyewear (eSight Corp., Toronto, ON, Canada). This device was originally launched commercially in 2013 and was registered with the US FDA as well as Health Canada and the European Database on Medical Devices. The eSight was designed to improve on previous devices by providing variable magnification, improved focus, improved contrast enhancement, and hands-free use. This semi-immersive device utilizes a virtual reality system to help patients with improved vision at all distances within 30 degrees of frontal viewing. One key upgrade from eSight involved the use of organic light-emitting diodes (LED) within its display, allowing for brighter images. Users can adjust functionality with a handheld remote that is connected to the headset.

Several studies have been conducted to assess what level of visual improvement eSight can offer patients. In an initial study by Wittich et al,[17] 51 patients were followed for 3 months of eSight use. The patient showed immediate improvements in visual ability, namely visual acuity, contrast sensitivity, and critical print size. Follow-up data showed a possible improvement in ADLs at 3 months. Another study by Wittich et al[18] later examined whether telerehabilitation with a low-vision therapist would benefit patients more than the self-training standard

offered by the eSight manufacturer. This later study revealed that patients experienced benefits within several weeks of usage, independent of training type. Together, these findings highlighted eSight's ease of use as well as its significant impact on patients' visual functioning. As such, it served as a key step forward in the landscape of low-vision wearable devices.

IrisVision

IrisVision (IrisVision Global Inc., Pleasanton, CA) is a smartphone-based, virtual reality HMD that restores areas of vision loss in patients with macular degeneration, diabetic retinopathy, Stargardt disease, glaucoma, and optic atrophy. Developed by a collaboration of inventors, the National Eye Institute, and Samsung and first available in 2017, the smartphone built into the headset captures images of the environment. Algorithms then remap those images to fill in information that otherwise would be missing due to central scotomas or peripheral field loss. Newer iterations of IrisVision include voice control and streaming capabilities, as well as a more lightweight design that allows for mobile use.

In a 2024 comparison of IrisVision against 2 other augmented reality devices, Ziru (Dodrotu, Oxford, UK) and NuEyes Pro 3 (NuEyes, Newport Beach, CA), IrisVision demonstrated significantly improved distance and near vision in all illumination settings with combinations of high and low luminance and contrast.[19] Another 2018 study comparing IrisVision to eSight and Jordy found that IrisVision provided a larger improvement in lines of distance visual acuity compared with eSight, and that it received the highest rank based on overall preference/performance, with 72% of respondents favoring it over eSight and Jordy.[15] Finally, a 2020 survey of commercial IrisVision users by the device's inventor found that 80% used the device for more than 3 hours a day, and 25% used it nearly full-time.[20] Familiarity increased use, with 50% of patients spending 3 times more time using IrisVision after 7 weeks of ownership.[20] In Schmidt et al's[16] comparison of 4 HMDs in Stargardt disease, previously mentioned in this article, IrisVision produced improvements in distance visual acuity, reading distance, and near visual acuity with high contrast. IrisVision was the only device that featured a net positive satisfaction rate with computer-related tasks.[16]

AceSight

Developed by a collaboration of Zoomax Technology, UCLA, and MIT, AceSight (Zoomax Technology Co., Ltd., Boston, MA) is an augmented reality HMD that uses a remote control to alter images presented on a semi-transparent display. A single central front-facing camera captures images and magnifies them up to 9×. The field of view is 90 or 45 degrees for each eye. It features algorithms that adjust the magnification and contrast of the display screen depending on the participant's specific visual deficits. AceSight also features a narrow mode for patients with peripheral vision loss—the size of the real-time image can be reduced by 0.5× or 0.25×, compressing a wide visual field into a smaller one corresponding to a patient's remaining visual field.

A 2024 study of AceSight's utility in patients with tunnel vision found that AceSight significantly increased both horizontal and vertical visual field diameters, with the horizontal field enlarging by about 15 degrees and the vertical by 8 degrees.[21] There was also a statistically significant improvement in visual acuity (logMAR 0.89 with AceSight versus logMAR 0.62 without). However, subjective experiences were more mixed—36% of participants thought AceSight was "helpful," 28% thought it was "a little help," and 46% chose "not helpful." Younger participants (below 60 years old) tended to find the device more helpful than older patients, echoing a demographic preference for HMDs that has been found in other studies. Schmidt et al[16] found that AceSight improved distance visual acuity and that AceSight was the only HMD of 4 that improved vision during near tasks at home. AceSight also performed relatively well with reading at a distance.

OcuLenz

The OcuLenz (Ocutrx Technologies, Irvine, CA) headset, not yet available commercially, uses AR to overlay high-contrast, pixel-manipulated images onto the user's remaining field of view. The technology uses embedded 4K cameras and algorithms to identify blind spots in each eye and then remap a missing image to another area with an intact visual field. As the disease progresses, the mapping algorithm continually refines the image placement. OcuLenz also features eye-tracking technology to help stabilize the display image at the location of remapping.

Eyedaptic

In recent years, Eyedaptic (Eyedaptic, Laguna Hills, CA) has developed and brought to market a group of augmented reality, video see-through HMDs designed for patients with low vision due to retinal disease. Unlike typical AR devices, these glasses do not display overlaid images. Rather, adaptive algorithms reformulate images from the environment by enhancing pixels and remapping areas lost to central scotomas. In addition, the relatively small frame of these HMDs allows patients with retinal disease to preserve the full use of their intact peripheral vision.

The original prototype was the Eye-01, introduced in 2017 and further described at ARVO 2018, 2019 and the CSUN Assistive Technology Conference in 2019. A single-arm crossover study of 14 patients with moderate visual impairment from AMD found that the Eye-01 improved patients' reading ability to a mean critical print size of 0.71 LogMAR, up from 0.96 LogMAR with near correction alone. In addition, the Eye-01 improved Timed Instrumental Activities of Daily Life (TIADL) by 2 times (308 s reduced to 171 s).[22]

The Eye2 was the first commercially released product, released in March 2020, with limited widespread adoption due to the concomitant start of the COVID pandemic. The Eye3 was then released in 2021, with new advancements in contrast sensitivity due to automatic

edge enhancement (BritexTM) and zoom (AutozoomTM). These new advancements were the first signs of AI being used in this technology.

Eye4 and Eye4XC brought further advancements in contrast sensitivity and were released in 2022. The Eye4 glasses have a lightweight design of 3 ounces, now achievable because the bulk of the processing power that was previously contained within the glasses is now contained within a linked smartphone (EyeSwitch) via a tethered cable. The 1080p displays of the headset each have over 2 million pixels and a 50-degree field of view. These displays feature auto zoom, image stabilization, and contrast enhancement. A prospective study of the Eye4XC in patients with binocular BCVA 20/70 to 20/400 due to diabetic macular edema found that the device improved best-corrected distance visual acuity and near visual acuity by two lines compared with only wearing prescription glasses.[23] In addition, wearing the Eye4XC improved mean contrast sensitivity by 2 units compared with only wearing eyeglasses. Furthermore, the addition of the EyeSwitch improved mean contrast sensitivity by 3 units compared with only wearing eyeglasses.

Eye5 advanced these same principles before release in 2023. It also included a small, embedded camera which serves to capture the environment and enhance the pixels to optimize a user's functional peripheral vision. Finally, the Eye6, which has yet to be released, has incorporated WiFi and 5G connectivity and uses large language model AI systems to enhance the visual experience for patients with low vision. This AI model has been designed to read text to speech and describe visual scenes in detail for patients with low vision. Furthermore, it is now being programmed to respond to nearly 100 languages.

Challenges

HMDs have been valuable resources for patients with life-altering low vision, yet there remain significant barriers to their function and widespread adoption. The limitations of the technology include battery life, the need for WiFi or Bluetooth connection, and bulky or uncomfortable fit that may limit prolonged or public use. Asymmetric vision loss or scotoma location can make it difficult to attain stereoscopic vision. Most importantly, each patient's visual deficit is unique. These devices will require individually tailored image-processing algorithms that continually optimize the visual experience, in both real-time and as patients' field of view changes over time. To this end, artificial intelligence is now being applied to some HMDs and represents the future of this technology. These technologies still have many limitations in their processing power, support networks, data safety, privacy, and reliability measures, and will need continued research and development for their technological, ethical, and legal framework.

Other significant factors preventing the adoption of existing HMDs include cost, patient discomfort, and social stigma. Although current HMDs provide many visual benefits, their cost may be prohibitive for the majority of low-vision patients. It is well known that patients with low vision are often financially disadvantaged compared with their sighted, age-matched peers. However, commercial advances such as the Apple Vision Pro, Meta Quest 3, and Magic Leap 2 give impressive market force to the development of vision aids. These companies offer a new class of premium hardware that may support many of the features that patients seek, such as voice control or built-in conferencing. This vulnerable patient population will be vastly aided by these commercial advances and by the manufacturing volumes that drive down costs. Considerations for reimbursement through healthcare policy and insurance may further mitigate the significant out-of-pocket expenses for patients.

Despite progress in making HMDs more lightweight and comfortable, users still find them uncomfortable and provocative of unpleasant symptoms. Surveyed users of an HMD that was the precursor to the IrisVision described symptoms of headache (17%), nausea (13%), and eye strain (38%).[24] Users of the SightPlus device also reported headache, sore eyes, nausea, and dizziness—with some reactions being severe enough that investigators terminated the study session early.[25] In Schmidt et al's[16] study, 2 users dropped out due to dizziness, double vision, and discomfort. In another study of AceSight, subjects commented on their desire for the device to be more portable and practical for outdoor use and further called for an increase in anti-shake functions to reduce dizziness, fatigue, and symptoms related to head movement.[20] In a survey by Lorenzini et al[26] regarding factors affecting HMD use, lack of headache was one of the factors that most consistently predicted sustained device use.

Finally, social stigma remains a significant barrier to the more widespread use of HMDs. In the Schmidt and colleagues study, 2 out of 6 participants used HMDs "seldom" at work, and 4 out of 6 participants did not use them at all at work.[16] Five of the 6 participants cited the appearance of the device as the reason they did not use it in a public space. However, HMDs are becoming smaller, lighter, and more discreet. With AR/VR displays becoming more commonplace among the general population, we anticipate that uptake among low-vision patients will only increase as HMDs become nearly indistinguishable from regular spectacles.

CONCLUSIONS

Researchers will continue to pursue both biological and nonbiological solutions for low vision. Head-mounted technologies can help patients today and may continue to improve visual function for patients in the future. These devices seek to deliver critical visual information intelligently and seamlessly in real-world conditions. Innovations in augmented reality, spatial computing, artificial intelligence, and optical systems will continue to improve the patient experience. Scalable manufacturing, affordability, and device functionality remain important barriers for researchers, industry leaders, and health care institutions.

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